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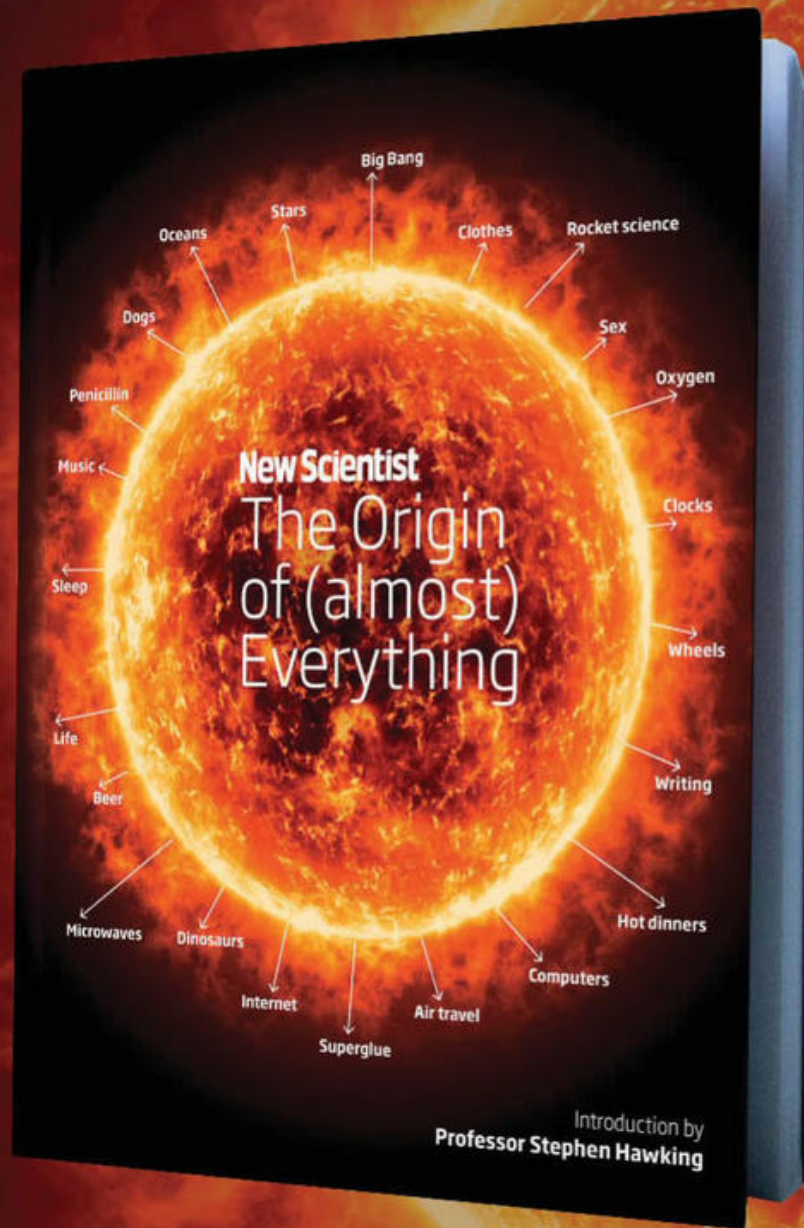
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Introduction by **Professor Stephen Hawking**

**New
Scientist**

VOL 3 / ISSUE 5
**MIND-EXPANDING
IDEAS**

**NEW SCIENTIST
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Deep exploration

Travel, it is said, broadens the mind. It certainly does, but not quite as much as science. To find proof of that, take a mind-expanding journey through this collection of classic articles from *New Scientist*, featuring some of the best science writers and thinkers discussing concepts that will make you think twice, if not thrice, and then walk away enlightened.

On your travels you'll encounter some of the world's biggest and boldest ideas. Did life originate light years away? Could we ever change the laws of physics? Could we travel through space-time? Do the multiverse – and an infinite number of other yous – exist? Could you cheat death by freezing your head? Or would you just be happy to be able to talk to your dog?

Chapter 1 is all about deep thoughts. Find out how the world's greatest minds deal with the universe's most mind-boggling concepts, from multiple dimensions to quantum reality. It will also give you a better handle on probability – although you might still be left scratching your head over the Monty Hall problem.

Chapter 2 identifies the key principles of the cosmos and the physics supporting it. It also explains why the laws that govern our universe are as they are, and what we still don't know. The questions we can't yet answer are many and varied: What came before the big bang? Why do we only move forward in time (or at least seem to)? We know a lot, but the gaps in our knowledge are even bigger.

Chapter 3 takes an alternative look at life and death. Everything in your world has an amazing story to tell, from where it originated to where it ended up. We also look at the not-always-obvious developments that have put

humans in control of their destiny, from cooking and fighting to cosmetics and the rule of law. Finally we meet the people who believe they can cheat death, and visit a facility in Texas that aims to realise their dream.

In Chapter 4 we look at the universe and our place in it. Was it made for us? Does it know we exist? Could we engineer or destroy it? We also revisit the multiverse, play a potentially fatal quantum version of Russian roulette and ask the question: is what we perceive only in our heads?

Finally, Chapter 5 takes a journey to the deep future. Where will we be in 100,000 years? Will we be on our way to the stars because we've run out of resources or need a new home? Will our species have evolved into something else? What could archaeologists from the future discover about us? We also consider whether there are immutable limits to human knowledge.

This collection presents both the improbable and the possible. It's our best guess at how our universe is structured and what our place in it is. It's the journey of a lifetime – for you and your descendants. Prepare to have your mind expanded.

Mick O'Hare, Editor

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CONCEPTS

Science is full of mind-blowing and counterintuitive concepts. To make any progress at all, scientists must get their heads around infinity, space, deep time, relativity and more.

Over the next 10 pages the people who perform these conceptual feats on a daily basis describe how they do it and provide some tips on how you too can think like a pro

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HOW TO THINK ABOUT

1 HIGHER DIMENSIONS



There's hardly a problem that physicists haven't tried to solve by adding extra dimensions to our everyday three of space and one of time: whether with crunched up dimensions too small to see, or the idea that our 4D world exists on a "brane" floating in an inaccessible higher-dimensional world.

How to envisage such things? Physicist Carlo Rovelli of the University of Aix-Marseille, France, doesn't personally have much truck with more than three spatial dimensions – "I do not think they exist," he says – but he finds extra dimensions easy enough to picture. "It is just a space where you can go up-down, left-right, ahead-back, but also in one other dimension, something like leftB-rightB," he says. "It is a bit like having many arms, like an Indian god."

Others are more circumspect. "Visualising higher dimensions is certainly harder," says Don Marolf of the University of California, Santa Barbara (UCSB). One standard trick is to start at the bottom and work your way up, extrapolating your understanding of lower dimensions to higher ones. The principle is illustrated in Edwin Abbott's 1884 classic novella *Flatland*. When the 3D Sphere passes through 2D Flatland, the inhabitants of the 2D plane perceive the sphere as a sudden dot that grows into a big circle before diminishing back into a dot again.

Even if this process of slicing a higher-dimensional object into a series of projections becomes impossible to envisage in more dimensions than three, it will always work in this way: simply add extra dimensions to your equations, supplementing the standard x, y, z and t with extra coordinates, say w or s . "In the end there is always mathematics," says Joe Polchinski, also at UCSB.

Polchinski's speciality is string theory, still the most favoured route to unifying quantum theory and general relativity, the two irreconcilable underpinnings of modern physics. Depending on what variant you choose, it requires 10 or 11 dimensions. The mathematics works fine. As to whether these dimensions actually exist – well, that's anyone's guess. **Anil Ananthaswamy**



2

HOW TO THINK ABOUT SPACE-TIME

Space-time. Often described as the fabric of reality, this four-dimensional amalgamation of space and time was set at the heart of physics by Einstein (see “Relativity”, page 14). But what is it?

A popular way of envisaging space-time is as a stretchy rubber sheet that deforms when a mass is placed on it, with the varying curvature analogous to the warping of space-time by gravity.

It's a picture that might lead us to believe space-time is itself something physical or tangible. But the physical manifestation of the dimensions we move through is, if anything, the fields they contain (see “Fields”, page 13). For most physicists, space-time itself is a lot more abstract – a purely mathematical backdrop for the unfolding drama of the cosmos. Martin Bojowald of Penn State University sees it as a mathematical entity called a manifold. The equations of general relativity allow us to calculate the evolution of this manifold, and so of the universe itself, over time. “The rubber sheet is a picture for such a manifold, so in an abstract way I am indeed using the analogy,” he says.

Don Marolf of the University of California, Santa Barbara, goes even

further. “Visualising the ‘shape’ of space-time is very useful,” he says. “But most of us don’t visualise it as something particularly physical. To the extent that we draw pictures, they are just chalk lines on the blackboard.”

One thing that unifies all of these conceptions of space-time is that it is a “continuum”, something that varies smoothly with no abrupt knobs, bumps or tears. But if we want to combine general relativity with quantum mechanics to create a unified theory of quantum gravity, that notion must change. In quantum gravity, space-time is made up of tiny discrete quanta just like everything else – making it a fabric with a discernible warp and weft.

“Fabric as opposed to a rubber sheet means that we are focusing more on what possible microstructures space-time may have,” says Bojowald. Carlo Rovelli of the University of Aix-Marseilles, France, visualises this woven microstructure as being made of “tiny fuzzy blobs”, the starting point of his theoretical investigations of quantum gravity. It’s still just a device, though: something that helps him work with the intangible. “If I do not have an image in my head, I cannot even start thinking,” he says. **Anil Ananthaswamy**



MARIO WAGNER

4

HOW TO THINK ABOUT COMPUTING



We all know what computers are, right? They sit on our desks and in our pockets, and put the smarts into everything from cars to washing machines.

That’s not wrong – and yet it’s not entirely right.

At its most basic, a computer takes information as an input, transforming it according to some predetermined rules into a different output. The digital electronic computers that rule

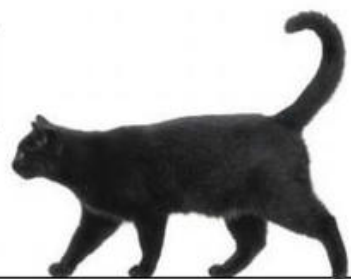
our world do this using little pulses of electric current. But there’s no reason it has to be that way. “An abacus allows us to compute by moving stones around,” says Peter Bentley at University College London. “If you can do that, I struggle to think of anything you cannot compute with.”

Sundials convert shadows to time, the liver regulates chemical outputs according to inputs, even rocks store mineral compositions for later breakdown and release: all of these things fit the broadest definition of

3

HOW TO THINK ABOUT

QUANTUM REALITY



I believe in an external physical reality beyond my own experience,” says Johannes Kofler of the Max Planck Institute of Quantum Optics in Garching, Germany. “The world would be there without me, and was there before me, and will be there after me.”

Given what we know about quantum physics, that seems a bold statement. The assaults that this most fundamental theory of reality makes on our intuition are legion: particles that exist as probabilistic wave functions in “superpositions” of multiple states or places, or at least seem to as long you don’t look at them; “entangled” particles that influence each other over vast distances of space when you measure one of them.

For Aephraim Steinberg at the University of Toronto in Canada, dealing with such troubling concepts is a matter of retraining our brains. “As much as we talk about ‘counter-intuitiveness’ of quantum mechanics, we just mean that it’s counter to the intuitions we have before we learn

quantum mechanics,” he says. After all, we aren’t that great at second-guessing aspects of classical reality, either: how many of us would naturally say that feathers and bricks fall at the same rate under gravity?

With quantum physics, though, it doesn’t help that the quantities used to describe objects seem to exist only mathematically. Visualising a wave function as a real thing is fine for a single particle, but things rapidly get more tricky. “Once you’re talking about more than one particle, the wave function lives in some high-dimensional space I don’t know how to visualise,” says Steinberg. He ends up having to break a complex quantum system down into parts. “But they’re all merely ways of chipping away at the abstract mathematical object I know provides the complete description.”

More fundamentally, though, if you accept quantum physics at face value then at least one of two dearly held principles from the classical world must give. One is realism, the idea that every object

has properties that exist without you measuring them. The other is locality, the principle that nothing in the universe can influence anything else “instantaneously” – faster than the speed of light.

For most quantum physicists, it’s realism that has to give, given all the evidence that the cosmic speed limit is never broken. The Copenhagen interpretation is the most widespread of the approaches that result, says Kofler. This demands that at least some properties of microscopic objects don’t exist prior to and independent of measurement. Alternatively, physicists resort to the many worlds interpretation, in which all possible results of a measurement happen, each spawning a different universe – whatever that means.

It’s fair to say that no one really gets all this. That means practitioners of quantum physics need to guard against relying too heavily on new intuitions and imagery, says Steinberg. “That’s exactly the point at which one develops a dangerous self-confidence.” **Anil Ananthaswamy**

a computer. “The notion of ‘computation’ currently appears to float dangerously free of its foundations,” says Mark Bishop of Goldsmiths, University of London.

One way out is to suggest a hierarchy of computing machines. At the bottom are “finite state machines”: things like traffic lights and elevators that do little more than cycle through a limited series of input and output states.

Digital computers fall into the category of Turing machines. As

conceived by Alan Turing in the 1930s, these read symbols from an infinitely long input tape and substitute them according to a set of rules, thereby simulating the behaviour of any conceivable algorithm. Basic though it seems, this still provides perhaps the best understanding of the limits of computation, says Bentley.

According to Turing’s model, though, there are well-defined problems that no computer can answer, such as the self-referential halting problem, which asks: “Will this

program stop?”. No computer can say yay or nay without actually running the program (and possibly stopping). Other problems, though theoretically computable, take an almost endless time to solve. “Computer science was born very conscious of its limitations,” says Christos Papadimitriou at the University of California, Berkeley.

Models of computing more powerful than Turing machines do exist; Turing himself speculated about them. Some people think biological processes might be able to implement

such “super-Turing” computation, accounting, perhaps, for some of our own excessive smarts. Others think that super-Turing models can only work by breaking the laws of physics as we know them.

If so, that suggests an intriguing and deep-seated connection between notions of computability and the workings of the universe. If we can’t quite get our head around computers, perhaps it is because we are sitting in the biggest of them all. Douglas Heaven

5

HOW TO THINK ABOUT INFINITY

Ian Stewart has an easy, if not particularly helpful, way of envisaging infinity. “I generally think of it as: (a) very big, but (b) bigger than that,” says the mathematician from the University of Warwick in the UK. “When something is infinite, there is always some spare room around to put things in.”

Infinity is one of those things with a preprogrammed boggle factor. Mathematically, it started off as a way of expressing the fact that some things, like counting, have no obvious end. Count to 146 and there’s 147; count to a trillion and say hello to a trillion and one. There are two ways of dealing with this, says Stewart. “You can sum it up boldly as ‘there are infinitely many numbers’. But if you want to be more cautious, you just say ‘there is no largest number.’”

Only in the late 19th century did mathematicians plump for the first option, and begin to handle infinity as an object with properties all of its own. The key

was set theory, a new way of thinking of numbers as bundles of things. The set of all whole numbers, for example, is a well-defined and unique object, and it has a size: infinity.

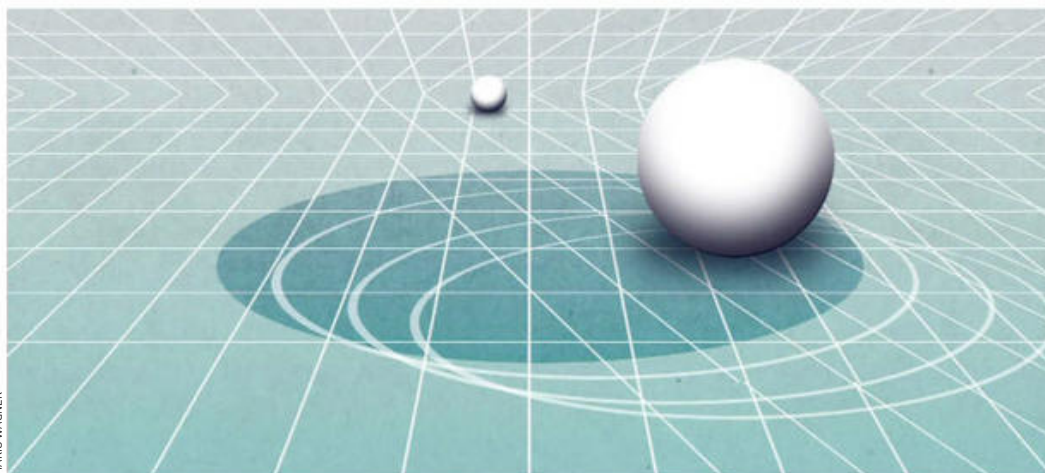
The sting in the tail, as the German mathematician Georg Cantor showed, is that by this definition there is more than one infinity. The set of the whole numbers defines one low-lying sort, known as countable infinity. But add in all the numbers in between, with as many decimal places as you please, and you get a smoother, more continuous infinity – one defined by a set that is infinitely bigger.

That is just the beginning. Hugh Woodin is a set theorist at Harvard University who has a whole level of infinity named after him, a particularly vertiginous level populated with numbers known as Woodin cardinals. “They are so large you can’t deduce their existence,” he says.

Such infinities help solve otherwise unsolvable problems in less rarefied mathematical

landscapes below. They are the ultimate abstraction: although you can manipulate them logically, you can’t write formulae incorporating them or devise computer programs to test predictions about them. Woodin’s notepads consist mainly of cryptic marks he uses to focus his attention, to the occasional consternation of fellow plane passengers. “If they don’t try to change seats they ask me if I’m an artist,” he says.

How closely our common-sense conception of endlessness matches the mathematical infinities isn’t clear. But if we can’t quite grasp boundarylessness, it probably doesn’t matter, says Woodin – however you slice it, infinity seems far removed from anything we see in the real world. Perhaps those enigmatic markings aren’t so different from those his fellow passengers might use after all. “It might be we’re just playing a game,” says Woodin. “Perhaps we are just doing some glorified sudoku puzzle.” **Richard Webb**



MARIO WAGNER

UNIVERSE
13.8 BILLION
YEARS OLD

6

HOW TO THINK ABOUT

DEEP TIME

In June 1788, Scottish geologist James Hutton took his colleagues John Playfair and James Hall to Siccar Point on the Berwickshire coast.

To unenlightened eyes, the rocky promontory would have appeared eternal and unchanging. But Hutton and his fellow travellers knew better. As Playfair later wrote: "The mind seemed to grow giddy by looking so far into the abyss of time."

Visit Siccar Point today and it still appears almost exactly as it did in 1788. Hutton realised that this continuity was an illusion, and that the sequence of events he could read in the rocks spoke of unimaginably slow changes occurring over mind-expanding stretches of time. The "angular unconformity" of rock layers of varying types and orientation could only have formed over tens of millions of years. It was a crucial piece of evidence in his theory of Earth's gradual evolution and the revolutionary concept of deep time.

Little more than a century earlier the primate of all Ireland, Archbishop James Ussher, had used the Bible and other sources to pinpoint the date of creation to Sunday 23 October 4004 BC. Isaac Newton disagreed: he thought the year was 3988 BC. Then, as now, deep time went deeply against the grain of common sense.

"Measuring things against a human lifespan is a normal and natural way to think," says John McNeill, an environmental historian at Georgetown University in Washington DC.

Through the heroic efforts of Hutton and many after him, we now know that Earth is around 4.54 billion years old and the

universe about 13.8 billion. Our world is almost inconceivably old.

Deep time was central to the development of the historical sciences – geology, evolutionary biology and cosmology – and remains so. "Their ruling ideas absolutely depend on dealing with deep time," says McNeill. Without it, we can't appreciate that some processes, whether the weathering of rocks, the evolution of species or the formation of galaxies, generally occur on timescales so slow as to be inappreciable within a human lifespan. "We might be misled into supposing all is stationary, as most people in most cultures have," says McNeill.

As Playfair found, trying to conceive deep time can induce vertigo, and our odd glimpses of it – ancient fossils dug from geological strata, pictures of star fields from the deep cosmos – can be hard to deal with. But for McNeill it is also liberating. "What it means to me is that we are all part of an unimaginably long chain of being, both human and non-human, and our own travails don't amount to a hill of beans."

Graham Lawton



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HOW TO THINK ABOUT

THE BIG BANG

Space is big, wrote Douglas Adams in *The Hitchhiker's Guide to the Galaxy*. "Really big. You just won't believe how vastly hugely mindbogglingly big it is." Too right: the edge of the observable universe is some 46 billion light years away. Within that volume there are anything between 100 and 200 billion galaxies, each containing hundreds of billions of stars.

If that weren't mind-blowing enough, according to the big bang theory – our best stab at explaining how it all came to be – everything exploded into being from nowhere, about 13.8 billion years ago (see "What came before the big bang?", page 46). An infinitesimal pinprick of unimaginable heat and density has slowly stretched and cooled into the cosmos we know today.

How can we get our heads around that? For cosmologist Martin Rees of the University of Cambridge there are two strategies: bury yourself in equations, or draw pictures. "I'd put myself in the picture camp," he says. He envisages the expanding universe by imagining himself at one node of a three-dimensional lattice stretching as far as the mind's eye can see, with the nodes linked by rods, all of which are expanding. You can visualise the universe moving away from you in all directions – while recognising you'd see the same thing from any other node. "You understand there is no central position," he says.

There's also no discernible edge: periods of accelerated expansion during the universe's earliest instants and in more recent aeons mean that the horizon of the observable universe is by no means the end of all things. Beyond it are galaxies we will never see because the intervening space is expanding too fast, so their light can never reach us. "I think it is fair to say they are retreating from us faster than the speed of light," says Rees.

Even more challenging is to envisage what came before the big bang. Our current conceptions of physics suggest the question makes no sense: as we rewind time to the very first instants, the intense concentration of energy jumbles up even space and time in a confusion of... stuff. "There is no direction of time, so there's no before and after," says Rees. "The analogy that's always made is it's like asking what's north of the North Pole."

Not that this stops some physicists trying. The theory of eternal inflation proposes that when the universe began in the big bang, it might just have been one of a multitude budding off from a larger entity – and that other universes might constantly be budding off our own. "Is there a beginning in that theory?" asks Rees. "If you have universes sprouting and they are governed by different physical laws, what then? That's where my intuition breaks down completely." Richard Webb

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HOW TO THINK ABOUT PROBABILITY



THE MONTY HALL PROBLEM

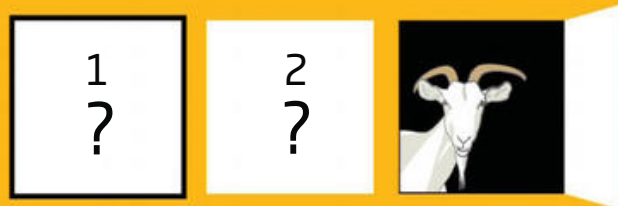
Suppose you're on a game show, and you're given the choice of three doors

"Pick a door"



Behind one door is a car; behind the others, goats

You pick a door, say **No. 1**, but you don't open it and the host, who knows what's behind the doors, opens another door to reveal a goat



The host then says to you,

"Do you want to switch to number 2?"

Counter-intuitively, you should **switch**. Here's why

YOU PICK						
1	2	3	HOST OPENS		You STICK	You SWITCH
Car	Goat	Goat	or	Goat	✓	✗
Goat	Car	Goat			✗	✓
Goat	Goat	Car			✗	✓
The fact that the host knows what is behind the doors affects your chances so: win ratio					1/3	2/3

The same applies if you pick 2 or 3

Probability is one of those things we all get wrong... deeply wrong. The good news is we're not the only ones, says John Haigh, a mathematician at the University of Sussex in Brighton, UK, and author of *Probability: A very short introduction*. "Many pure mathematicians claim that probability has many unreasonable answers."

Take the classic problem of a class of 25 schoolchildren. How likely is it that two of them share the same birthday? The common-sense answer is that it is not implausible, but quite unlikely. Wrong: it's actually just under 57 per cent.

Or the celebrated Monty Hall problem, named after the former host of US television game show *Let's Make a Deal*. You're playing a game in which there are three doors, one hiding a car, two of them goats (see illustration, left). You choose one door but don't open it; the host of the game then opens another, revealing a goat. Assuming you'd rather win a car than a goat, should you stick with your choice or swap?

The naive answer is it doesn't matter: you now have a 50-50 chance of striking lucky with your original door. Wrong again.

But if probability makes even experts grumble, how do we get it right? Simple, says mathematician Ian Stewart of the University of Warwick in the UK: do things the hard way. "The important thing with probability is not to intuit it," he says. Think carefully about how the problem is posed and do your sums diligently, and you'll arrive at the right answer - eventually.

With the birthday problem, the starting point is to realise that you're not interested in individual schoolchildren, but pairs. In a class

of 25, there are 300 pairs to consider and, in most years, 365 days on which each might share a birthday. Factor all that in, and you end up crunching some truly astronomical numbers to arrive at the answer. "Any coincidence like that is remarkable in itself, but when you ask how many times it would happen, that number is so vast it's not remarkable at all," says Haigh.

With the Monty Hall problem, meanwhile, the chance you chose the right door in the first place is 1/3 - and that doesn't change whatever happens afterwards. Since the host has revealed a goat, there is now a 2/3 probability that the car is behind the other door - and you are better off swapping.

There are a few caveats: if the host is so devious as only to open a door if you chose the right one in the first place, you'd be mad to swap. Ditto if you want a goat rather than the car. That illustrates another important rule in thinking about probability, says Haigh. "It is very important to know your assumptions. Very subtle changes can change the outcome."

All this is very well when the boundaries of the problem are clear and the possible outcomes quantifiable. Toss a fair coin and you know you have a 50 per cent chance of heads - because you can repeat the exercise over and over again if necessary.

But what about a 50 per cent chance of rain today, or of a horse with even odds winning a race? No amount of expert advice can help us assess the true worth of such "subjective" probabilities, which are fluid and often based on inscrutable expertise or complex modelling of an unpredictable world. Sometimes you do just have to go with your gut instinct - and be prepared to be wrong. Richard Webb

HOW TO THINK ABOUT

MATHEMATICS

Mathematics is like a language – but one that, thanks to its inbuilt logic, writes itself. That’s how mathematician Ian Stewart sees it, anyway. “You can start writing things down without knowing exactly what they are, and the language makes suggestions to you.” Master enough of the basics, and you rapidly enter what sports players call “the zone”. “Suddenly it gets much easier,” Stewart says.

“You’re propelled along.”

But what if you don’t have such a maths drive? It’s wrong to think it’s all down to talent, says mathematician and writer Alex Bellos: even the best exponents can take decades to master their craft. “One of the reasons people don’t understand maths is they don’t have enough time,” he says. “It’s not supposed to be easy.”

Sketching a picture of the problem helps. Take negative numbers. Five sheep are easy enough to envisage, but what

about minus five? “We can’t see the minus five sheep, so you can’t get your head around it,” says Bellos. It was only when someone had the bright idea of arranging all the existing numbers 0, 1, 2, 3... on a line that it became obvious where the negative numbers fitted in. Similarly, complex numbers – 2D numbers that underpin the mathematics of quantum theory, among other things – only really took off with the advent of a “complex plane” in which to depict them.

Analogies also help. If thinking about ellipses oppresses you, think about a circle that’s been squashed and work from there, says Stewart. Overall, contrary to the impression of mathematics as a discipline of iron logic, the best way to attack a problem of any sort is often to get a brief overview of it, skip over anything you can’t work out and then go back and fill in the details. “A lot of mathematicians say it’s important to be able to think vaguely,” says Stewart. **Catherine de Lange**

10

HOW TO THINK ABOUT

FIELDS



Frank Close has a question. “If you step off the top of a cliff, how does the Earth down there ‘know’ you are up there for it to attract you?” It’s a question that has taxed illustrious minds before him. Newton’s law of gravitation first allowed such apparently instantaneous “action at a distance”, but he himself was not a fan, describing it in a letter as “so great an Absurdity that I believe no Man who has in philosophical Matters a competent Faculty of thinking can ever fall into it”.

Today we ascribe such absurdities to fields. “The idea of some physical mediation – a field of influence – is more satisfying,” says Close, a physicist at the University of Oxford. Earth’s gravitational field, for example, extends out into space in all directions, tugging at smaller objects like the moon and us on top of a cliff; the Earth itself is under the spell of the sun’s gravitational field.

But hang on: what exactly is a field? On one level, it is just a map. “Ultimately, a field is something that depends on position,” says Frank

Wilczek, a theoretical physicist at the Massachusetts Institute of Technology. A gravitational field tells us the strength of gravity at different points in space. Temperatures or isobars on a weather chart are a field. A field is a mathematical abstraction – numbers spread over space.

But there is more to it than that. Witness what physicist Michael Faraday saw in the 19th century, and many a schoolkid has since: iron filings neatly ordering themselves along the lines of a magnetic field, reaching out into space from the magnet itself and influencing nearby objects (though at the speed of light, not instantaneously). “It made a huge impression on Faraday, that this strange thing had a physical reality,” says Wilczek.

Arguably the modern world is built on the principle of electromagnetic induction that Faraday developed out of his new understanding of fields: magnetic fields and electric fields power the motors of our civilisation. A mere abstraction?

The modern era has shed some further light on fields, but also added

confusion. Quantum fields – ultimately, the electromagnetic field is one – have tangible products in the form of particles, which pop up as disturbances within them. For the electromagnetic field, this entity is the photon. The Higgs field, long postulated to pervade empty space and to give elementary particles their mass, was discovered in 2012 by squeezing out its particles in high-energy collisions.

But quantum fields are complicated beasts, formed of “superpositions” of many classical fields. That’s far away from anything we can envisage as a map, or delineate as neat lines. “At that point I have to rely on equations,” says Wilczek, who won a Nobel prize for his work on the quantum fields of the strong nuclear force.

One thing’s for sure: fields are everywhere. Quantum theory teaches us that even seemingly empty space is a roiling broth of fields and their associated particles. “The idea that nothing’s there is extremely naive,” says Wilczek. Aside from anything else, fields are the proof that nature does indeed abhor a vacuum.

Richard Webb

HOW TO THINK ABOUT RELATIVITY

11

Space and time used to be so simple. You trundled around reasonably freely in the three dimensions of the one, and experienced occasional heartache at the remorseless forward march of the other. C'est la vie.

Or is it? Einstein revolutionised our perceptions a century ago when, in his theories of relativity, he first forbade anything in the cosmos from travelling faster than the speed of light, and then bundled both space and time into one unified space-time that can be warped by gravity (see "Space-time", page 8). The contortions introduced by Einstein's special and general theories make intervals in both space and time dependent on where we measure them from. Two observers with flashlights in fast-moving trains might both measure the other to have flashed their flashlight first – and both be right from their own point of view.

The blockbuster movie *Interstellar* was based on premises that Einstein made technically plausible, if not (yet) technologically feasible: that by travelling close to the speed of light, or moving in an intense gravitational field such as that of a black hole, we age more slowly than those we leave behind on Earth. We don't need to travel that far to see less dramatic effects of relativity in action. Astronauts on the International Space Station age a little less because of the velocity at which they travel, and a little more for enjoying less of the gravity of mothership Earth. The effects don't quite cancel out. Velocity wins, leaving each ISS astronaut who completes a six-month tour of duty 0.007 seconds younger than someone who stayed on Earth.

For most everyday purposes, such effects matter not a jot. But for cosmologists like Sean Carroll of the California Institute of Technology in Pasadena, who peer deep into the cosmos, relativity is a crucial consideration. He often resorts to drawing a diagram. "As far as special relativity goes, it's very natural to think in terms of pictures," he says. Relativity can seem full of paradoxes if we don't first think carefully about how our own motion affects our perception of how time is passing for others – but also how others might see our time passing differently, too.

Carroll has a few rules of thumb to guide his own perceptions. "Basically, time is kind of like space, but not exactly," he says. The main difference is that

whereas in space a straight line is the shortest distance between two points, in time it is the longest. The way to minimise the time you experience between two events that occur at the same point in space is to move as far and as fast as you can in the interim. "If you zoom off near the speed of light, then zoom back, you will experience less time than someone who simply sits still," says Carroll. So time passes slowly when you're having fun. **Richard Webb**

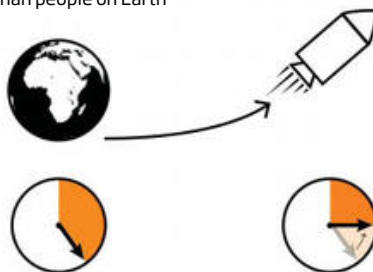
INTERSTELLAR SCIENCE

Einstein's theories of relativity – special and general – encompass two effects that influence our perception of space and time

SPECIAL RELATIVITY

Moving clocks run slower

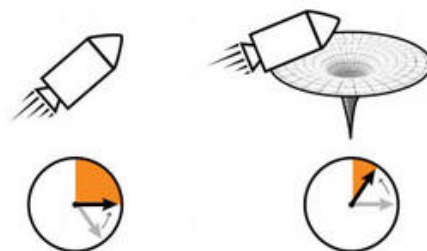
To an outside observer, the crew of a spaceship travelling close to the speed of light will age less than people on Earth



GENERAL RELATIVITY

Clocks run slower in high gravity

A spaceship entering a high gravitational field like that of a black hole will experience even less time



12

In a cave, a bear gives birth to two cubs one long dark night. In the morning, the weak winter light reveals something strange: the cubs' fur is white, in stark contrast to the dark fur of their mother. They are freaks... or are they?

What is evolution? Easy, you might think: it's the way living organisms change over time, driven by natural selection. Well, that's not wrong, but it's not really how evolutionary biologists think of it.

Picture those bear cubs. Here we see a dramatic physical change, but it isn't evolution. Among black and brown bears, white bear cubs are not that uncommon. But white bears don't have more cubs than other bears, so the gene variants for white fur remain rare.

Among one group of brown bears living in the Arctic, though, white fur was an advantage, helping them sneak up on prey. There white bears thrived and had more offspring – their "fitness" increased – so the proportion of white bears rose until the entire population was white. This is definitely evolution. It happened as polar bears evolved from brown bears a few million years ago.

So although we tend to think about evolution in terms of the end results – physical changes in existing species or the emergence of new ones – the key concept is the spread of genetic variants within a population.

The results of this process can appear purposeful. Indeed, it is convenient to talk as if they are: "polar bears evolved white fur for camouflage". But it all comes down to cold numbers: a random mutation that boosts fitness spreading in a population.

HOW TO THINK ABOUT EVOLUTION



STEVEN KAZLOWSKI/SCIENCE FACTION/CORBIS

When does a dramatic physical difference become evolution?

What's more surprising is that even mutations that don't increase fitness can spread through a population as a result of random genetic drift. And most mutations have little, if any, effect on fitness. They may not affect an animal's body or behaviour at all, or do so in an insignificant way such as slightly altering the shape of the face. In fact, the vast majority of genetic changes in populations – and perhaps many of the physical ones, too – may be due to drift rather than natural selection. "Do not assume that something is an adaptation until you have evidence," says biologist Larry Moran at the University of Toronto, Canada.

So it is wrong to think of evolution only in terms of natural selection; change due to genetic drift counts too. Moran's minimal definition does not specify any particular cause: "Evolution is a process that results in heritable changes in a population spread over many generations."

It does not even have to involve many generations, says Michael Kinnison of the University of Maine in Orono, who studies how

living species are evolving. Evolution occurs almost continuously, he says. It usually takes time for populations to change significantly, but sometimes it happens very fast, for instance when only individuals of a particular genetic type survive some catastrophe, or when only tumour cells with a particular mutation are not killed by a cancer drug.

In these cases, there is no need to wait for the survivors to reproduce to determine that the population has changed. "I would say evolution occurs whenever some process changes the distribution of heritable traits in a population, regardless of the timescale," Kinnison says. "While evolutionary biologists like to treat evolution as a generation-to-generation process, that is often more a matter of convenience than reality."

Suppose those white bear cubs somehow reached an island and founded a new bear population. The interbreeding of white bears always produces white offspring, and thus being white would be normal there. So we can boil down the concept of evolution to just six words: Evolution is what makes freaks normal. **Michael Le Page**

13 HOW TO THINK ABOUT ALIEN CONTACT

We must realise that there are other worlds in other parts of the universe, with races of different men and different animals." That was the Roman poet Lucretius, writing in the 1st century BC.

Only in the past few decades have we grasped the truth of the first part of that statement, thanks to planet-hunters such as NASA's Kepler Space Telescope. Thousands of suspected planets have already been spotted outside our solar system – including an Earth-like planet called Proxima b orbiting our nearest star. Stars nursing planets seem to be the rule, not the exception. With hundreds of billions of stars in our galaxy alone, that's a lot of worlds. Surely it's only a matter of time before we confirm the second part by finding life signs (see "What if we are not alone?", page 19).

Perhaps. Life on Earth has required billions of years to evolve organisms capable of asking such questions, and that process has been anything but inevitable. Other life, if it exists, may be nothing like life as we know it.

This is the central dilemma of searches for ET, says Jeffrey Scargle of the NASA Ames Research Centre in Moffett Field, California. "You can't assume nothing because then you don't even know how to start looking, but if you assume too much then you're biased and you're not open to

finding a lot of things that might be there."

So alien life might be carbon-based, and ultimately get its energy from starlight through a process like photosynthesis. Or it might work entirely differently, in which case searches for the metabolic products of carbon-based life in far-off atmospheres – oxygen, methane and the like – will never be a smoking gun.

Perhaps more conscious signals from similarly questioning civilisations are a better bet. "It's natural to assume that any intelligent civilisation would have that concept of needing to wave a flag," says Scargle. He is studying Kepler data for signs of "star-tickling": variations in a star's brightness induced by aliens using it as a beacon. But as far as decoding any message goes, he's sceptical: even our idea of what counts as a regular pattern might not be shared by others.

Scargle's former colleague Lucianne Walkowicz points out that even looking for something like radio transmissions might be assuming too much. "Earth is getting quieter as it gets more advanced, not louder," she says. And what if we were to pick up an incontrovertible signal of alien civilisation from, say, 10,000 light years away? That would tell us of something existing 10,000 years ago – a long time by the measure of human civilisation to date. Perhaps even a lively cosmos is a lonely one. **Douglas Heaven ■**

WORLD TURNED UPSIDE DOWN

Every now and then an idea comes along that upends how we see ourselves and our place in the cosmos. Earth goes round the sun. We are descended from apes. Our hearts are merely pumps made of meat.

The rumblings of the next revolutions in our thinking may already have started. Here are 10 “what ifs” with the potential to change us forever.



WHAT IF... MOST OF REALITY IS HIDDEN?

MY GOAL is simple,” Stephen Hawking once said. “It is a complete understanding of the universe, why it is as it is and why it exists at all.” That, in a nutshell, is the scientific manifesto – ambitious, maybe, but at least in theory possible.

But what if it isn’t?

There’s no shortage of indications that there might be limits to how far we can penetrate with science. String theory, for example, regarded by many physicists as our best bet for a unified theory of reality, proposes between 10 and 26 space-time dimensions, many of them wrapped so up tightly as to be virtually inaccessible. That could slam the door on answering mysteries such as why gravity is so weak, or how mysterious dark energy is apparently accelerating our universe’s expansion.

The Large Hadron Collider at CERN near Geneva, Switzerland, is one place where researchers are seeking hints of hidden dimensions. Does it matter if we occupy the cheap seats in the cosmic theatre? David Berman at Queen Mary University of London is relaxed about the idea. “In some sense, science has always been about approximating reality,” he says.

More perplexing, perhaps, is that our universe may be just one of countless others. Space-time’s headlong expansion might have led individual

patches to become so far detached as to be independent. Some part of such a vast “multiverse” would be bound to have the life-friendly laws of our own universe – but also our physics could be entirely unrepresentative of the whole.

We can’t yet conceive how we might access other parts of the multiverse, but proof it exists might not be beyond us, says Alexander Vilenkin of Tufts University in Medford, Massachusetts. Budding universes bumping into each other as they expand might leave marks visible from Earth, perhaps in the cosmic microwave background, the ancient radiation that suffuses our sky. That would be just the latest reassessment of our place in the cosmos. “Long ago, humans thought they were at the centre of the universe, but ever since Copernicus, it was all downhill. We had better get used to it.”

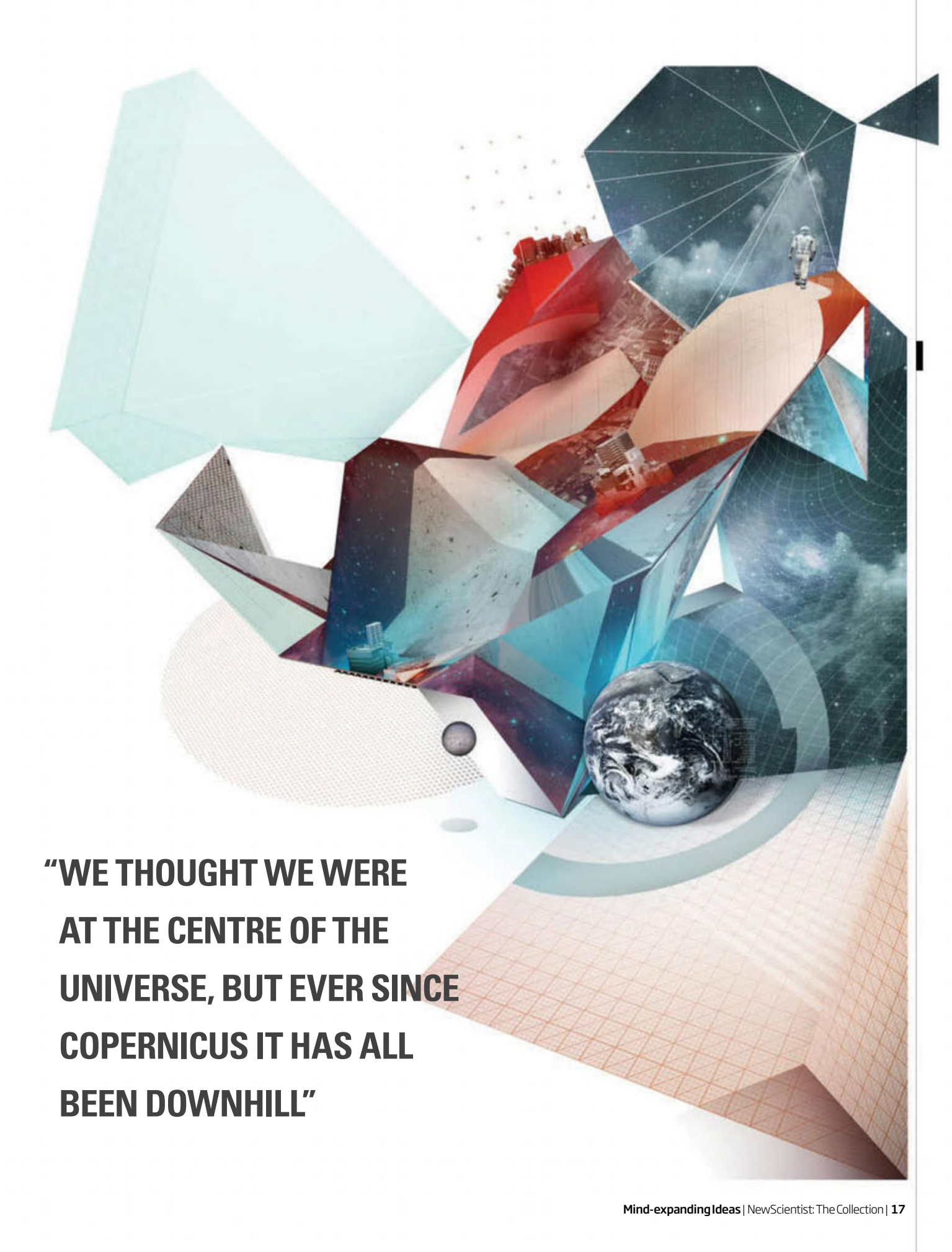
With the quantum multiverse, things are even more unsettling. The strange consequences of quantum theory – like cats being dead and alive at the same time – are explained away by the many-worlds interpretation, which says the universe splits every time we look at it. That creates a new universe for every possible outcome of our observation.

But what does it mean for morality if there are countless universes out there, all containing near-identical copies of us? Are we responsible for them all? That depends, says David Papineau, a philosopher at King’s College London. On the one hand, if you got away with something here, don’t think that you did elsewhere. “If your behaviour really made nasty results likely, then there are many other branches of reality on which people have been injured and maimed because of your recklessness.” At the same time, if sensible behaviour backfires in this world, take heart that most other yous are probably better off.

Such questions may seem like idle speculation at the moment – but they might not always be, says Berman. Perhaps one day, we will travel to another universe or visit worlds in another dimension, and judge things for ourselves. “There’s an enormous arrogance associated with people who put limits on what we might one day be able to see,” he says. “Why should the human lifetime be a natural unit for studying the progress of science?”

Gilead Amit

SKIZZOMAT

The image is a complex, abstract collage. It features a large, light blue, translucent geometric shape on the left. In the center, there's a red, angular structure that resembles a cityscape or a mountain range. To the right, a dark blue, angular shape contains a figure of a person in a spacesuit standing on a ledge, looking out at a starry sky. Below the red structure, a globe of the Earth is visible, surrounded by various geometric shapes in shades of blue, green, and orange. The overall composition is layered and dynamic, with a mix of organic and geometric forms.

**"WE THOUGHT WE WERE
AT THE CENTRE OF THE
UNIVERSE, BUT EVER SINCE
COPERNICUS IT HAS ALL
BEEN DOWNHILL"**



WHAT IF... WE DISCOVER WE CAN SEE THE FUTURE?

HUMAN beings are adept mental time travellers. Our ability to envisage how things might be in the future, which seems unmatched by any other species, is arguably what has made us the cultured and civilised animals we are. But if visualising possible futures is a game changer, being able to predict the future would be nothing short of revolutionary.

Debate has long raged about whether that is even possible. According to one school of scientific thought, known as determinism, it is. Given enough data about each atom in the universe, we can know tomorrow's football scores with as much certainty as yesterday's.

This mindset suffered a couple of blows during the 20th century. First, Heisenberg's notorious uncertainty principle said it was impossible to know everything about a quantum system such as an atom. Second, chaos theory taught us that the future behaviour of any physical system is extraordinarily sensitive to small changes – the flap of a butterfly's wings can set off a hurricane on another continent, as the saying goes.

But even if it's theoretically impossible, in practice we might get as close as makes no difference. Computers are already producing ever more accurate simulations of

future reality, from tomorrow's weather to long-term climate trends to the eventual fate of our galaxy. Extrapolating from current number-crunching capabilities, near-perfect climate prediction, for example, should be possible within a century or so, says climate scientist Gavin Schmidt of NASA's Goddard Institute for Space Studies in New York City.

Such soothsaying ability might not play to our advantage, says Matteo Mameli, a philosopher at King's College London. Predictive software might ultimately deprive us of that evolutionarily hard-won ability to think creatively and improvise our way out of dangerous situations. Alternatively, unrestrained by any fear of failure, our hubris may accelerate our destruction of the world around us.

The outcome might depend on who has access to the predictive tools, says Timothy Pleskac, a psychologist at the Max Planck Institute for Human Development in Berlin, Germany. In the wrong hands, they might help prop up dictatorships or establish commercial monopolies. But more socially minded governments could use them to ready their citizens for challenges such as approaching environmental disasters.

Or, Pleskac thinks, our supremely adaptive minds might finally find themselves overwhelmed by such omniscience – and reject it in favour of a quiet life. "They might say all that information is there, but I don't want to have access to it," says Pleskac. "It may be quite adaptive to be ignorant. People may just want to be left alone." **Gilead Amit**

**"BEING ABLE TO SEE
THE FUTURE MIGHT
NOT PLAY TO OUR
ADVANTAGE"**



WHAT IF... WE LEARN TO TALK TO ANIMALS?

LAST year, a New York court ruled that Hercules and Leo, two research chimps at Stony Brook University, had no right to legal personhood. But the fact that such a case made it through the courts at all shows our new willingness to consider the issue of personhood for other species. "Efforts to extend legal rights to chimpanzees... are understandable; some day they may even succeed," wrote judge Barbara Jaffe.

Steven Wise, a lawyer at the Florida-based Nonhuman Rights Project, which



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WHAT IF... WE ARE NOT ALONE?

brought the lawsuit, argues that if chimps are declared legal persons, they should be granted rights to protect their fundamental interests. "That would certainly include bodily liberty and likely bodily integrity as well," he says. We could no longer keep chimps in captivity, never mind subject them to intrusive experimental procedures.

If chimps were given rights, we might expect other intelligent species, such as killer whales and elephants, to follow. But why stop there? Our ideas about the inner lives of other animals - their capacity for suffering, autonomy and self-awareness - are based largely on analogy with ourselves: how would we like it if it was us?

But what if those animals could tell us? What if a dog or dairy cow could let us know how it felt about its lot in life? The idea may not be as far-fetched as it seems. There are many examples of communication between apes and their human keepers. Researchers are busy decoding dolphin language. And cognitive scientists are beginning to study emotional states in animals. It may only be a matter of time before more meaningful communication between species is possible.

Would we still eat meat once that happens? If we could converse with pigs, say, how could we justify slaughtering them by the billion, however humanely? And

where should the line be redrawn? Would we still eat fish? Many of us might shun meat and animal products entirely.

Legal rights for animals would affect environmental efforts too. Conservationists would have to put down the gun, says biologist Marc Bekoff, formerly of the University of Colorado in Boulder. Right now, most people take a utilitarian view, considering it acceptable to kill members of one species to save another or to safeguard an ecosystem. "But if we accept that these animals are sentient beings and ascribe greater value to each individual life, you have to have alternatives," says Bekoff, a leading voice in the compassionate conservation movement. He insists a "do no harm" approach is possible, although others argue it would make us too sentimental to do much good.

How would we weigh an animal's life against a human one? Research on animals leads to treatments that save human lives, making a blanket ban on animal testing unlikely. But asking scientists to limit the pain and suffering they inflict will no longer be enough, says Bekoff. Scientists would have to make the case that the benefits for humans outweigh the harm to the animal. At the very least, lots more species would get their day in court.

Daniel Cossins

THANKS to the Kepler Space Telescope, we know the galaxy could hold as many as 30 billion planets similar to our own. The next generation of eyes in the sky, such as the James Webb Space Telescope, slated to launch in 2018, will search the atmospheres of such exoplanets for signs of life. Some think it's just a matter of time before we find out we're not alone. In April 2015, NASA's chief scientist Ellen Stofan predicted we would have "strong indications of life" on other planets by 2025. If she is right, how will we deal with it (see "How to think about alien contact", page 15)?

What we detect will make a big difference to how we react, says Steven J. Dick, a former NASA historian and astrobiology chair at the US Library of Congress in Washington DC. Any discovery that is less obvious than little green men landing during the World Cup final is likely to be met by years of questions and examination. Sara Seager, a planetary scientist at the Massachusetts Institute of Technology who is searching for another Earth, agrees. It will probably take time to confirm any initial findings, she says. "There may not be an 'aha' moment."

A chemical imbalance in an exoplanet's atmosphere could be a sign of microbial activity. But an indirect result such as this will probably have only a short-term impact, says Dick. The apparent discovery of Martian nanofossils in meteorite ALH84001 in 1996 led to a media frenzy, and even US congressional hearings, before the furore died down in the face of increasing scepticism. Most now

CLOCKWISE FROM BOTTOM: REX/SHUTTERSTOCK; ALESSANDRA SANGUINETTI/MAGNUM PHOTOS; SUPERSTOCK; JEAN-LUC CHAPAIN/AGENCE VUCCAMERA PRESS

think that the meteorite does not hold the remnants of ancient alien life.

A decoded broadcast from intelligent aliens would be altogether different. Scientists and governments would have to assess whether the message was threatening and what, if anything, should be sent as a response. It would pose a challenge to certain religions too, says Dick. "Does Jesus have to be a planet-hopping saviour to all ETs?" Some people might see intelligent aliens as saviours themselves, giving rise to new religions. Others may simply celebrate them as species that overcame their provincial squabbles to explore the universe.

In the longer term, even slight evidence of extraterrestrial life would spark a quest to understand the universal principles of biology, says Dick. We may find answers to questions such as: does life arise wherever the conditions are right, or is it a freak accident? Are there other types of genetic code? Does life always require carbon or water? Is Darwinian natural selection universal, or are there other forms of evolution?

Perhaps most significantly, it would be the decisive blow to the idea that humans are the centre of the cosmos or the reason for its existence. Instead, we would have to acknowledge our place as just one tiny branch of a vast galactic tree of life. "I hope people will find a sense of peace and an understanding that we are not alone," says Seager.

MacGregor Campbell



If aliens got in touch, how should we reply?



WHAT IF... WE DON'T NEED BODIES?

MINDS result from bodies, but that link can be compromised. If I severed my spinal cord at the neck, I'd get no inputs from most of my body, says Michael Graziano, a neuroscientist at Princeton University. "But I'm still a person, I still have experience, I can still think."

What if we could separate mind from body entirely? Many now believe that we will transfer our minds on to computers, possibly within a matter of decades. "I would say that it's not only possible, it's inevitable," says Graziano.

What would life as an upload be like? We'd still need outside stimulation. Cut off entirely, a brain would suffer sensory deprivation, says Anders Sandberg at the University of Oxford. "It's going to fall asleep, then hallucinate and probably gently go mad. You need to give it a way of interacting with the world, although it doesn't have to be the real world."

Being able to transfer minds into a computer would change how we valued a life. Having multiple backup copies of ourselves might make life less precious. "You kill one of them, so what?" says Graziano. "There's a whole bunch more." Murder may no longer be a heinous crime when we can resurrect the dead. The same goes for victims of freak accidents, says Sandberg. Just boot up the last save and the only thing lost may be a few recent memories.

And if you think we are living in a hyperconnected world today, think again. Artificial brains would give connectivity a whole different meaning. "Forget texting, you can as good as stick a USB port in your head and

communicate directly with somebody else," says Graziano. "Now, we get into a totally different network of minds that doesn't resemble anything we know." Instead of inferring what is going on in someone else's head, we could share thoughts like we share digital files.

A big concern will be who controls the computers that run the brain simulations. In principle, those running the machines could make copies of you, says Sandberg. "They could run you on a secret system with no connection to the internet and force you to do a lot of stuff you might not want to do." We will need to drastically improve our software security in general, he says. "If it was a world where anybody could be hacked or copied at any time by unknown parties,





it'd be a bit too scary to live in."

Technical issues will abound. We may make mistakes during the upload process, and have warped brains sitting in computers. "Do you want a library of bad copies that you have some weird obligation to?" says Sandberg. The ethical conundrums become even more complicated if we assume your original brain and body stick around. Would virtual brains have equal moral and legal status?

Such questions are unlikely to be resolved in a hurry. "In many ways, we would become post-human," says Sandberg. "We'd have made the leap from being part of the animal kingdom to going into an entirely new kingdom, and we don't know what to call it yet."

Anil Ananthaswamy



WHAT IF... WE HAVE NO FREE WILL?

OUR moral sense is based on an assumption so fundamental it seems unassailable: that we are masters of our own destiny. But the more we unpick the subtle knot tying conscious experience to the brain, the shakier that assumption feels.

The free will debate is an old one (see "Do we have free will?", page 33), but in the 1980s psychologist Benjamin Libet really stirred things up. He performed an experiment that revealed a signal in the brain moments before his subjects felt a conscious intention to move a finger. Although Libet's work remains controversial, it raises a big question: is our unconscious brain really in the driver's seat, with our consciousness a mere passenger?

Even if we're driving, we may be on rails. Split-second life-or-death decisions - a police officer choosing to fire a gun, say - are often made too quickly for conscious deliberation to play a part. Instead, such choices may be guided by hardwired, unconscious bias.

What if a breakthrough in neuroscience

stripped us of free will? One outcome may be a loosening of morals. In experiments, people behave more selfishly and dishonestly if they are persuaded beforehand that free will is largely an illusion. They are also more likely to treat wrongdoers leniently, offering a hypothetical criminal a shorter prison sentence than they would otherwise have done. It's harder to ascribe blame to an automaton, after all. But these behavioural changes only last until the powerful feeling of our own agency reasserts itself.

On the other hand, belief in free will tends to be strengthened by considering a scenario in which someone acts immorally. Joshua Knobe of Yale University and his colleagues argue that our powerful belief in free will is bound up with a fundamental desire to hold others responsible for their harmful actions. In other words, belief in free will is required to justify punishment. And there is some evidence that fear of punishment is what keeps societies from breaking down.

Legal punishment for the purpose of retribution would make much less sense if the idea of free will were jettisoned, says Azim Shariff at the University of California in Irvine. But it might still serve a practical need as a deterrent. "Just as we make efforts to avoid the negative consequences of other natural phenomena like hurricanes and rat infestations, so too can we make efforts to incapacitate transgressors to stop them causing further harm," he says.

So we would probably keep our legal systems in place. Faced with the prospect of punishment, our brains work to keep us out of jail - consciously or unconsciously.

The loss of free will may be a harder pill to swallow when things get personal and our emotions come into play. "Thinking about a guy being mean to your sister is likely to motivate people to reject that neuroscience breakthrough," says Shariff.

Knobe agrees. "If people discovered that there was no free will, they would undoubtedly come to think very differently at an abstract level," he says. "Yet research suggests this sort of abstract reflection would have shockingly little impact on the way people actually treated each other."

In any case, hanging on to a strong belief in our own agency has its upsides. It is linked to a greater sense of satisfaction and self-efficacy, higher commitment in relationships and greater meaningfulness in life. Free will is dead? Long live free will!

Sean O'Neill

**"MURDER MAY NO
LONGER BE A HEINOUS
CRIME WHEN WE CAN
RESURRECT THE DEAD"**

7

WHAT IF... WE CAME FROM SPACE?

HOW did life begin? Charles Darwin speculated that it happened in "some warm little pond". Since then, many other possible crucibles have been identified: deep underground, in the open ocean, by hydrothermal vents on the ocean floor, on a radioactive beach and on the surface of a lump of clay. The hypotheses have little in common except for one thing: they take it for granted that Earth's life must have arisen at home.

What if it didn't? In the early 1970s, astronomers discovered that space was full of complex organic molecules, some of them forming part of the comets and meteorites that occasionally crash-land on Earth. Life also seems to have arisen here with improbable haste. Almost as soon as it was habitable, Earth became inhabited. Could the transition from prebiotic to biotic chemistry really have happened so fast?

The observations reignited an alternative account of how life began, first proposed in 1871. Panspermia holds that life got going somewhere else – perhaps on Mars, perhaps further afield – and was carried to Earth on a comet or meteorite. The idea remains an unproven hypothesis on the fringes of mainstream science. But the tide is turning, according to Chandra Wickramasinghe of the University of Buckingham, UK, one of the scientists who, along with Fred Hoyle, revived panspermia in the 1970s. "This was conjecture in the past, purely theoretical, but now we have evidence for it," he says (see "Four hints of panspermia", right). "It's changing, slowly but surely."

According to Wickramasinghe, the galaxy is teeming with life, and our biosphere is just part of a vast, interconnected cosmic ecosystem. Genetic material and even living

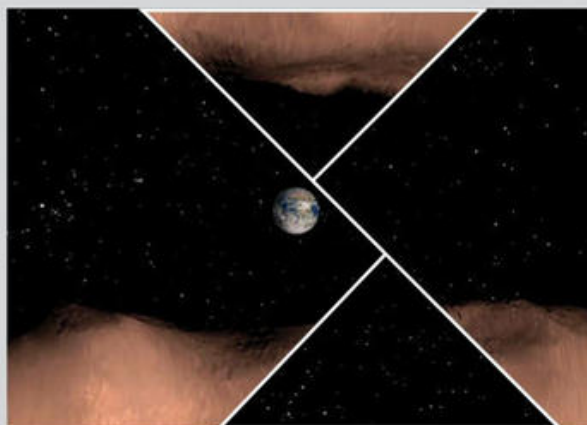
organisms are constantly exchanged between Earth and neighbouring star systems. Evolutionary change is largely driven by novel genetic material arriving from space, most likely in the form of viruses. Others are a little less ambitious, arguing merely that life first evolved on Mars. "I think the case for Mars as the origin of Earth life is pretty good," says Peter Ward, an astrobiologist at the University of Washington in Seattle.

Nonetheless, confirming that our distant ancestors were extraterrestrials would have a profound effect. "It would mean a re-evaluation of biological dogma," says Wickramasinghe. "Darwinian evolution is not a closed box. We have to regard evolution on our planet as the expression of something that has taken place over a vast region of space."

Socially, the biggest effect would probably be on religion. "It's a big blow," says Ward. "For some religious fundamentalists, it is an axiom that there is but one life and it is here on Earth." Wickramasinghe agrees that religions will be troubled, but not for long. "My guess is that leaders would be able to incorporate it into their existing theology – they've always been remarkably adaptable in taking on new developments."

Wider society would follow suit – and the effects could be positive. "Undoubtedly there would be resistance and denial," says Wickramasinghe. "Humans are very conservative. But ultimately, we'd come to think of ourselves not as terrestrial creatures, but as creatures of the cosmos. And the sympathy that we now feel for things that are happening across the planet would extend on a cosmic scale."

Graham Lawton



CLOCKWISE FROM BOTTOM: JAMES BRICKWOOD, BERNARD DESCANPS, DAVID SAUVEUR/AGENCE VU / CAMERA PRESS



FOUR HINTS OF PANSPERMIA

Sky-high bugs

In 2013, a balloon was flown into the stratosphere during the Perseid meteor shower. It returned with samples of microorganisms found 27 kilometres up, too high to have been lofted from Earth's surface.

Alien "fossils"

Numerous meteorites contain enigmatic structures that some have interpreted as fossilised bacteria.

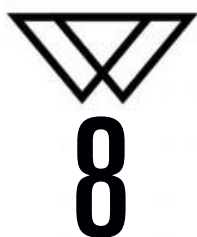
Lifelike light from space

The infrared light coming from many distant astronomical objects matches the kind that biological materials would give off.

Red rain

In 2001, Kerala in India was showered with reddish rain that contained unusual cell-like structures. The rain followed a sonic boom that may have been a meteor breaking up in the atmosphere.

"CONFIRMING THAT OUR DISTANT ANCESTORS WERE EXTRATERRESTRIALS WOULD HAVE A PROFOUND EFFECT"



WHAT IF... INTELLIGENCE IS A DEAD END?

OUR intelligence, the very trait we like to think makes us the pinnacle of evolution, could be our undoing. "Human beings tend to think being clever is such a good thing, but it might be that from an evolutionary perspective, being stupid

is much better," says philosopher Thomas Metzinger of the University of Mainz, Germany.

Humans have evolved a unique form of intelligence, with cognitive complexity unseen in other species. This has been the secret behind our agricultural, scientific and technological progress. It has let us dominate a planet and understand vast amounts about the universe. But it has also brought us to the brink of catastrophe: climate change looms and a mass extinction is already under way, yet there is little sign of a concerted effort to change our ways.

Our troubles could be compounded by the fact that human genetic diversity is abysmally low. "One small group of chimpanzees has more genetic diversity than the entire human species," says Michael Graziano of Princeton University. It's not unthinkable that a global disaster could wipe us out.

For this, we have an awkward double-act to blame. Metzinger argues that we have reached this point because our intellectual prowess must still work alongside hardwired primitive traits. "It is cognitive complexity, but without compassion and flexibility in our motivational structure," says Metzinger.

In other words, we are still motivated by some rather basic instincts, such as greed and jealousy, and not by a desire for global solidarity, empathy or rationality. And it's unclear whether we will evolve the necessary social skills in time to thwart planetary disaster.

Another part of the problem is that our intelligence comes with so-called cognitive biases. For instance, psychologists have shown that humans pay less attention to future risk compared with present risk,

something that makes us routinely take decisions that are good in the short term but disastrous in the long term. This may be behind our inability to fully fathom the risks of climate change, for example.

Humans also have what philosophers call existence bias, which influences our view of the value of life – it's better to exist than not. Ultimately, we tend to focus on the positives. But what if our intelligence were to develop in a way that meant we lost such biases?

In fact, super-intelligent aliens may have already achieved that. With a balanced outlook no longer weighted to the short term and a clear-eyed view of suffering, such a life form could decide that life is just not worth it. "They may have come to the conclusion that it's better to terminate their own existence," says Metzinger.

Could that explain why we haven't yet made contact with an alien intelligence? "Possibly," he says.

Anil Ananthaswamy



LEFT: STOCKTREK IMAGES/GETTY; RIGHT: DANIEL A. SANDS/AURORA PHOTOS



WHAT IF... THE UNIVERSE IS AN ILLUSION?

SOMETIMES, perceiving something as real doesn't cut it. With the shimmering image of a hologram, the illusion is clear enough. That 3D representation is a trick of the light, a projection of information encoded in just two dimensions. But it would be a bit of a shocker if we found out that the entire universe were made that way.

We're not close to proving that, still less working out the implications. But a groundswell of work in theoretical physics suggests it's a distinct possibility.

The story really begins in the 1990s. Physicists were struggling to tame the intractable mathematics of string theory – our best stab at forcing gravity to play nicely with the other three forces of nature – when they discovered a cunning trick. Under certain circumstances, by subtracting one from the number of dimensions in the universe you were dealing with – in other words, treating it like a hologram – gravity could be made to disappear.

The best-researched instance of this “holographic principle”, known as the AdS/CFT correspondence, only works in a complex 5D space-time bent back on itself rather like the surface of a Pringle. The trick has proved surprisingly useful, not just in string theory but also to elucidate the workings of practical things like superconductors, and explain such stubborn problems as why particles have mass.

But last year, Daniel Grumiller of the Vienna University of Technology in Austria and his colleagues supplied evidence that the principle also applies

in a “flat” space-time akin to our own universe – albeit with two spatial dimensions, not three. “This is non-trivial evidence in favour of flat-space holography, but far from being a proof,” he says.

Craig Hogan, a physicist at Fermilab near Batavia, Illinois, is out to get that proof. If the holographic principle applies in a flat universe like ours, space-time itself should start to look fuzzy at a certain scale, like a hologram viewed too close. He and his colleagues have built a device at Fermilab, known as the Holometer, to scout for this “holographic noise”. It ramped up to full power in 2014.

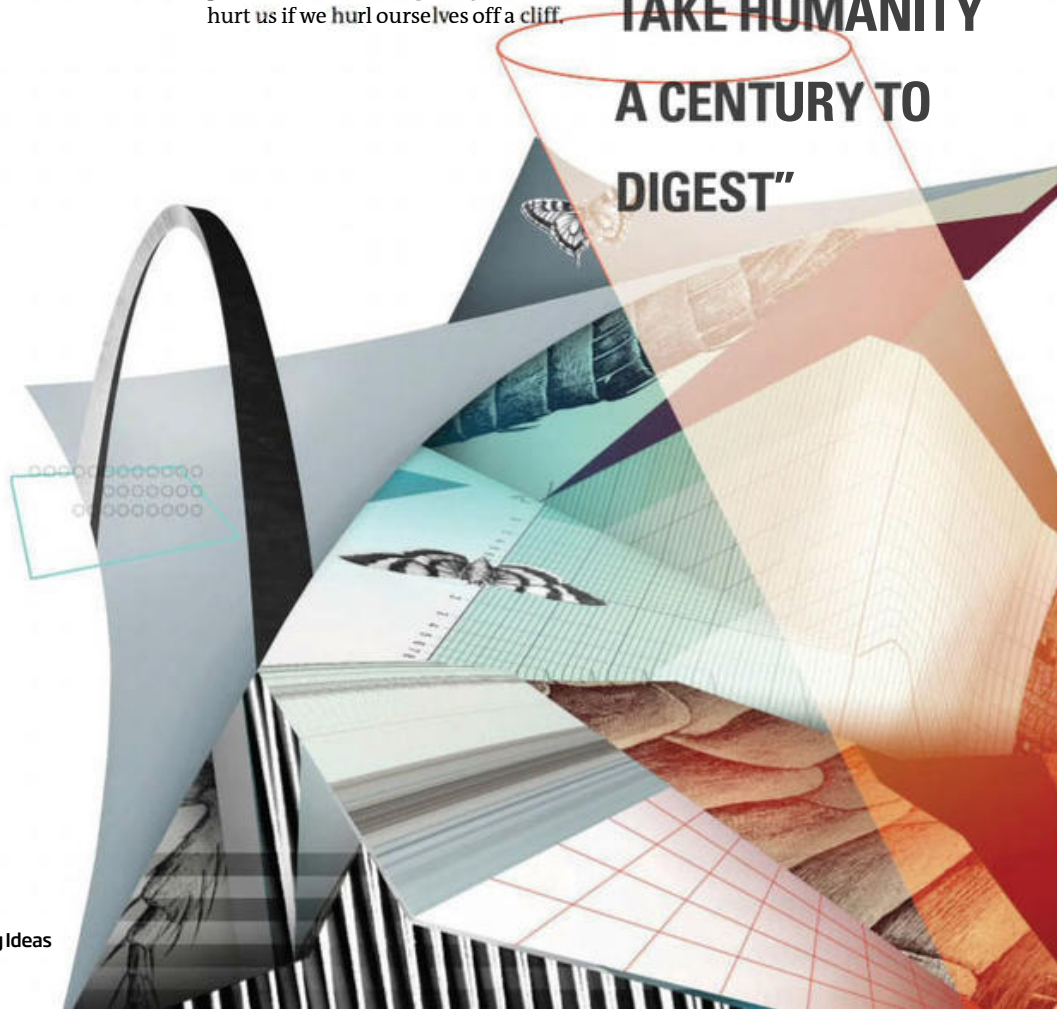
Any evidence for the holographic principle would be revolutionary, he thinks. “It is fundamental because it will go beyond the same basic ideas of geometry we have used for over 2000 years, since before Euclid.”

How will it change us? Practically, perhaps not much: we'll still perceive what we call three dimensions, and the phenomenon we call gravity will still hurt us if we hurl ourselves off a cliff.

But Grumiller thinks it could spark a sea change akin to the one started by Copernicus 500 years ago – plus, eventually, a similar puzzlement about how we were fooled for so long. “For the way we picture the universe and ourselves as part of it, the realisation that one of our dimensions and gravity are ‘illusions’ is very profound,” he says. “I estimate it will take at least a century for humanity to digest it.”

Richard Webb

**“REALISING THAT
ONE OF OUR
DIMENSIONS IS
AN ILLUSION WILL
TAKE HUMANITY
A CENTURY TO
DIGEST”**





Evidence for God could throw the world's religions into disarray

10

WHAT IF... WE FIND GOD?

THE equations are checked and rechecked. Finally, physicists throw up their hands and declare that the big bang must have had a cause – a prime mover that created the universe. Or perhaps God simply shows up on Earth in full supernatural glory. As shocks to the system go, it couldn't get much bigger.

There's no denying we have a God-shaped void in our heads. What if it were filled? Would our increasingly secular world see a mass conversion? Perhaps, but it is far from clear what people would convert to. In fact, organised religions would probably be thrown into disarray. If God could come in any number of guises, whatever this entity turned out to be would be unlikely to fit our narrow range of existing ideas.

We might also think that proof of God would be egg on the face of atheists. Perhaps – but for many, the idea of God is not only unbelievable, but also distasteful. The writer Christopher Hitchens, who called himself an “anti-theist”, detested the idea

of a cosmic chaperone watching our every move. If this being did present itself to us, we could see atheists start a revolution against God.

Ultimately, our reaction would depend on the nature of the evidence, says Joel Robbins, an anthropologist of religion at the University of Cambridge. Big changes would only come from a dramatic confirmation, he says. “It would take something like Jesus or aliens turning up on Earth and saying, ‘Hi, I’m your creator.’”

Although religion might take a hit, we could expect a boom in theological debate. At the top of the agenda would be morality, suffering and death – subjects often sidelined to academic backwaters, says Stephen Bullivant at St Mary's University in London. For example, if suffering exists despite there being an all-powerful God, does that mean suffering is somehow necessary in the universe? Or does it instead say something about the nature of this God?

There may also be a swing towards fatalism. There is evidence that religious people often simultaneously invoke natural and supernatural explanations for events such as sickness and death. People will take medicine even when they believe God is controlling the course of their illness, for example. Proof of God's existence might tip the balance away from medical explanations of sickness and encourage people to feel that when you get ill, that's it – your time has come.

Knowing that a physical entity set off the big bang would help cosmologists, says Alexei Nesteruk, a cosmologist and theologian at the University of Portsmouth, UK. It would prove once and for all that the universe is not eternal.

There are two broad theories that suggest the universe isn't eternal. Inflationary cosmology says that universes pop up like bubbles within a high-energy vacuum with repulsive gravity. And conformal cyclic cosmology says that parallel universes continually collide, move apart and collide again, each collision seeming like a big bang. A God might shed light on which of the competing models of our universe – or multiverse – is correct.

Ultimately, though, Nesteruk thinks proof of God is impossible, if we take this to mean evidence of an uncreated being. Faced with such an entity, we would always ask, “Well, who created you?”

Joshua Howgego ■

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► **metaphysics, n. pl.**

The branch of philosophy that deals with the first principles of things, including abstract concepts such as being, knowing, substance, cause, identity, time and space

LET'S GET METAPHYSICAL

The biggest questions are normally left to philosophers: How do I know I exist? Do we have free will? What is reality made of? Why, for that matter, is there anything at all? Now, though, scientists are increasingly claiming them as their own...

HOW DO I KNOW I EXIST?

The short answer is you don't. Consider this: with every passing moment, we get closer to creating intelligent machines, maybe even conscious ones. If we can do this, could someone – or something – else do it too?

Philosopher Nick Bostrom at the University of Oxford highlighted this idea in 2003, arguing that if humans were one day able to create simulations populated with conscious beings, it's at least possible that we, too, are living in such a simulation. Since then, that possibility has, if anything, become more realistic. There are projects seeking to build entire animal brains from scratch, modelled exactly on living ones, down to individual neurons and the myriad connections that interlink them. When very simple versions were given robotic bodies, lo and behold, they behaved like the creatures they were modelled on. It's probably only a matter of time before we create virtual beings inside computers.

In all likelihood, we will never find out whether or not we are simulations ourselves. But one thing is clear, says philosopher Thomas Metzinger of the University of Mainz in Germany: each of us has a robust experience that "I exist". Perhaps a slightly more manageable problem is to figure out where that experience comes from.

Clues come from neuropsychological conditions such as Cotard's syndrome, in which people are convinced that they do not exist. In 2013, Adam Zeman of the University of Exeter, UK, and colleagues reported their studies of a person with Cotard's. His brain scans showed important anomalies. One was in a brain network normally associated with internal awareness, including the awareness of our body and its emotional state. Activity in

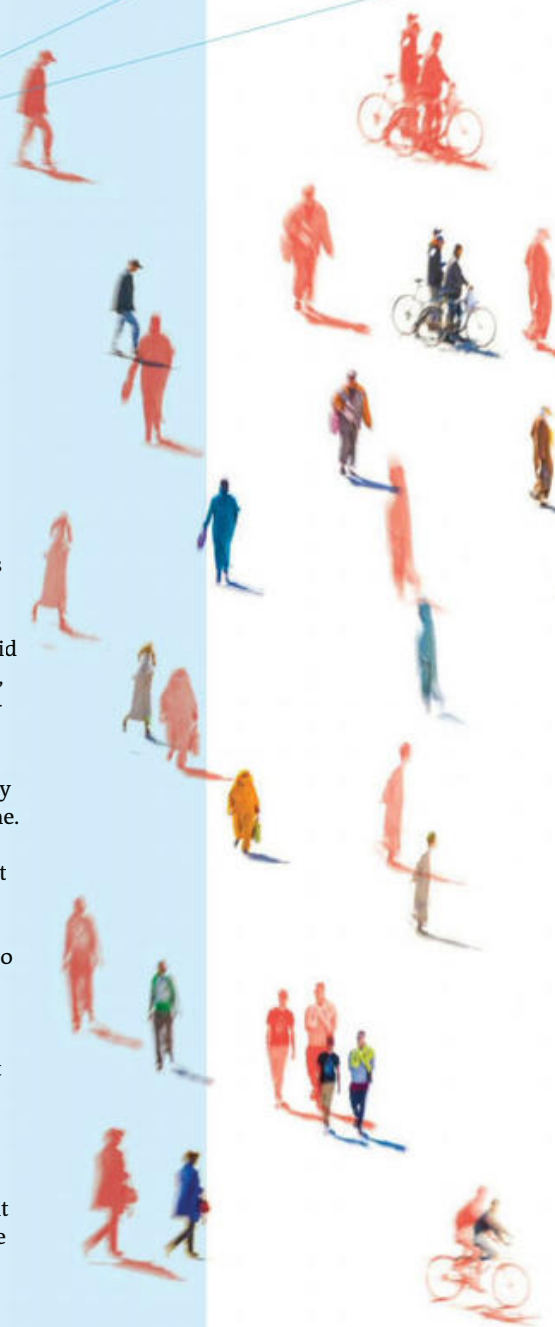
this network was low, down to levels seen in people who are minimally conscious. The researchers speculated that this created a perception of non-existence which the man could not discount because other parts of his brain responsible for rational thought were also damaged.

The findings suggest that by creating a vivid perception of our body and its various states, our brain generates the feeling of existence – and any malfunction in this mechanism can cause us to question it.

How this all happens could be explained by the idea that the brain is a prediction machine. It is continually being assaulted by signals from the body and its environment and must predict what's causing them. For example, when you are walking by the coast, the brain has to be able to perceive that you are about to come to a cliff – if you don't, you may fall off the edge. It does this by creating internal models of the body and the environment. To make accurate calculations, the brain must maintain prior knowledge and keep testing the integrity of its models. "The brain is a system that is continually trying to prove its own existence," says Metzinger.

He thinks this prediction machinery might be compromised in people with Cotard's. "The prediction error can never be cancelled out, [and this] attacks one of the most abstract and highest priors – 'I exist' – and makes that crumble away." Of course, all of this certainty and doubting could still be part of a simulation. In which case, says Metzinger, "What I'd want to know is, what the heck is the hardware that the simulation is running on? Is it God's brain or the Devil's?"

Anil Ananthaswamy





WHAT IS CONSCIOUSNESS?

In Cotard's syndrome, the feeling of existence corrodes but something more fundamental does not (see "How do I know I exist", opposite). Even though people with this rare condition feel they don't exist, there is still an "I" experiencing that feeling. What is that "I"? One answer is that it may be a by-product of consciousness itself.

René Descartes was convinced that the body and conscious mind are two different substances: the first is made of matter, the latter is immaterial. His ideas influenced neuroscience until a few decades ago, but the field has moved on. Today, it is widely accepted that our brains give rise to consciousness.

But how? That is a raging debate. At its heart is what philosopher David Chalmers at New York University termed the "hard problem" of consciousness: how can physical networks of neurons produce experiences that appear to fall outside the material world? As Thomas Nagel, also at New York University, put it in the 1970s: you could know every detail of the physical workings of a bat's brain, but still not know what it is like to be a bat.

FRANÇOISE HILLEMANN/PIANPICTURE

Broadly speaking, those trying to solve the hard problem fall into two camps, according to psychologist and philosopher Nicholas Humphrey. There are those who think that consciousness is something real (see "Does consciousness create reality?", page 87) and those who say it's a mirage, and so dismiss the problem entirely.

Mind trickery

The former camp argues that consciousness is a fundamental component of the universe, one that exists alongside matter and has properties which, perhaps conveniently, cannot be explained by our present understanding of physics. If taken to the extreme, says Chalmers, this idea can lead to panpsychism, the view that all matter – even inanimate objects like rocks – is imbued with some degree of consciousness.

Even without tackling that particular Pandora's box, this camp faces a challenge. We know conscious thought can influence the body; a conscious desire to move your arm results in physical movement. But the fundamentals of how this happens remain hazy.

Those on the other side say the hard problem creates one where there is none. "It's an unsolvable mystery, because the problem is ill posed," says neuroscientist Michael Graziano of Princeton University. He argues that consciousness is nothing but a trick of the mind. What's more, the brain doesn't just create the illusion of

consciousness but also the feeling that there is a separate, immaterial "I" having a conscious experience. In other words: there is no need to explain strange interactions between material and immaterial things because the immaterial things don't really exist.

For Graziano, Tufts University philosopher Daniel Dennett and other "materialists", the real issue is not solving the hard problem but explaining how the brain accomplishes this trickery. Graziano resolves this by saying that consciousness is "the brain's way of describing to itself what it means to pay attention to and deeply process a signal".

The argument goes like this: we must pay attention to our environment to survive. As a result, our brains have become skilled at representing the world around us. Somewhere in the course of evolution, they began representing objects as having immaterial properties, and in so doing generated the mirage of consciousness.

Ultimately, most materialists take the view that after we die and our brains and bodies have decomposed, there is nothing left. That must mean that our prevailing sense of a separate, immaterial "I" was also an illusion.

Which brings us back to the previous question: although you may know beyond doubt that you exist – and indeed it is very possible that you are not a simulation – the "I" you perceive yourself to be could still be an illusion.

Anil Ananthaswamy

"You may know beyond doubt that you exist, but your 'I' could still be an illusion"

WHY IS THERE SOMETHING RATHER THAN NOTHING?

German philosopher Martin Heidegger's angst-ridden non-answer to what he called "the fundamental question" was that a fear of nothing was the defining feature of the human condition. We certainly seem scared that nothing is some kind of universal default. But why should we presume that nothing is more likely than something? After all, if we accept that we exist to ask the question, then we've proved something exists. It's a whole lot harder to prove that nothing can exist.

It's tempting to think that modern physics has made this line of reasoning easier. According to quantum field theory, even the vacuum of space is a lively soup of particles and fields popping up out of nowhere. This kind of random fluctuation is thought to have ultimately created our cosmos of stars, planets and existential worriers out of the quantum vacuum – admittedly abetted by some

as-yet-unexplained happenstance, such as a period of faster-than-light inflation in the early universe, and matter somehow winning out against its evil twin, antimatter (see "Unruly penguins", page 54).

But there's a huge flaw in this logic: the quantum vacuum is not nothing.

And even if there were no quantum vacuum filling it, empty space would be anything but nothing. According to Einstein's relativity, space moves, bends, snaps and has holes in it just like a tangible, material thing. Even old-school physics admits it has a property: size. "When we say there is an absolute vacuum between Earth and the moon, that doesn't mean there is nothing," says physicist David Deutsch of the University of Oxford. "No distance between us and the moon – that would be disastrous."

Within this context, the idea that something can come from the "nothing" of free space is



not a problem, says physicist Paul Davies of Arizona State University, Tempe. "The ballyhoo about a universe popping out of the vacuum is a complete red herring," he says. "It just dodges the real issue, which is the prior existence of the laws of physics." More specifically, the question becomes why these laws exist instead of any other set, including no set at all.

"Even if the answer to why there is something rather than nothing were because of how quantum field theory works, the question would become why are the laws of quantum field theory as they are," says Deutsch. One answer may be because a universe built on this basis is particularly prone to producing conscious observers who ask what they think are probing questions. A popular idea is that all

the other possible laws of physics – including no laws – exist elsewhere in a "multiverse" of all possible worlds (see "What if most of reality is hidden?", page 16).

In that case, why a multiverse? In the end, says Deutsch, physicists are going to have to accept they can only ever shift the goalposts on this one. "It's a philosophical question and that's that." He thinks this is actually a good thing. Even if science could reveal an ultimate answer to why stuff is, we shouldn't want it. "We can't have a magic formula that resolves all problems," he says. "That would be a disaster; thinking would become pointless."

For him, the question is best explained by an old gag. "Why is there something? Because if there were nothing we'd still be complaining."

Richard Webb





WHAT IS THE MEANING OF LIFE?

The harsh answer is “it has none”. Your life may feel like a big deal to you, but it’s actually a random blip of matter and energy in an uncaring and impersonal universe. When it ends, a few people will remember you for a while, but they will die too. Even if you make the history books, your contribution will soon be forgotten. Humans will go extinct; Earth and the sun will be destroyed. Eventually the universe itself will end. Against this appalling reality, how can a human life have any real meaning?

This is one reason why belief in a god (or gods) is so popular: it softens the brutality of existence by imbuing the universe with meaning. Some theologians have even claimed that the pointlessness of life without God is evidence for God’s existence. In fact, there is no objective evidence for this (see “Can we ever know if God exists?”, page 37). So let us

put that comfort blanket aside and ask: in an indifferent and ephemeral universe, does human existence have any meaning at all?

In some interpretations of quantum mechanics, the universe only comes into being when we observe it, and the act of observing it actually determines what happens next by forcing reality into one of many possible outcomes. A wilder interpretation – called the many worlds hypothesis – claims that every time you make a decision, the universe replicates itself. You enter one universe and an alternative you enters the other. If true, your universe is created by the choices you make. How’s that for meaningful?

Just ask

Critics might argue that there is no more evidence for these ideas than for the existence of God. In any case, the meaning they provide is rather impersonal and abstract. But you don’t have to be creating universes to find meaning in life.

Recently, psychologists have hit on a novel way to discover whether life has meaning: ask people. When asked to rate how meaningful and purposeful their lives are, most people respond positively and rate their own sense of meaning and purpose as being greater than other people’s. In other words, despite the ultimately futile nature of human life, it feels pretty meaningful to those living it.

This finding has been criticised for being entirely subjective and for failing to capture a “true” or “higher” meaning, such as leaving a legacy or changing the world. But according to Laura King, a psychologist at the University of Missouri who studies meaning, that is self-serving, elitist nonsense. If people say they find meaning in life, who is to argue? We will never get objective data on the matter anyway.

Others point out that we are constantly searching for meaning, which suggests we do not have it. King sees no contradiction. “You can think of meaning like oxygen. Do I have plenty now? Yes. Am I going to keep on wanting plenty of it? Yes. You’re not going to stop wanting it because you already have it.”

“The philosophical question has always been: is there a meaning to life? What is the meaning of life?,” says King. “My goal is to think about meaning with a little ‘m’, in the real world, in everyday people’s lives. Then we can start thinking about it in a less highfalutin and more everyday way, to understand it as a human experience.” Feel better now?

Graham Lawton

WHERE DO GOOD AND EVIL COME FROM?

The 3-month-old baby was snatched from its mother's arms, killed by a bite to the forehead and eaten. The act was carried out by a mother and daughter who were members of the same close-knit community as the baby. They were later implicated in at least two other cases of infanticide and cannibalism.

By any standards of morality, this killing spree would be labelled "evil". But the attackers and their victims were chimpanzees living in Gombe Stream National Park, Tanzania. When primatologist Jane Goodall first reported it in 1975, she called it "barbarous murder". Can a chimpanzee be evil? Or, for that matter, good?

Philosophers have long wrestled with the nature of good and evil. Are they an inseparable duality? Are some things inherently good or evil? These questions seem too abstract to be answered by science. But by asking questions such as "why are animals altruistic?" and "why do chimps sometimes violently kill one another?", biologists have arrived at an explanation that applies equally well to humans. Underlying good and evil is the neutral hand of natural selection.

"Both 'evil' and 'moral' behaviour could serve one's inclusive fitness interests, depending on the individual and the circumstances," says Bernard Crespi, an evolutionary biologist at Simon Fraser University in British Columbia, Canada. Inclusive fitness refers to the genes you share with close relatives, which are passed on to their offspring. It is why some animals have evolved to do things like help siblings raise their young. Even though the helper is not raising its own brood, the shared genes benefit. What appears at first to be a selfless act is selfish at the genetic level.

Other things that appear purely altruistic are also better explained by a long-term benefit to the do-gooder. For example, blood donation is often cited as a totally selfless act, but one study found that it is more likely to be an act of self-interest. People who believe in the potential personal benefit of blood banks are more likely to donate than people who think mainly of their benefit to society.

"Good" behaviour, in other words, is often about personal gain – which casts something of a shadow on the concept. "Evil" behaviour might be the same thing. Take those infanticidal chimps. Subsequent observations

suggest that such acts occur at times when competition for food and other resources is higher – so killing the competition means more bounty for your own genes.

Josephine Head, a biologist who witnessed horrific chimp violence in Loango National Park in Gabon, says the behaviour of our closest living relative gives us a window into the roots of some human violence. "The tendency for group violence between males, and the strong 'us and them' mentality we attach to everything, can be traced back to this adaptive behaviour in apes," she says.

Extreme behaviour may be influenced by evolution in other ways. Money is sometimes paid to the families of suicide bombers, for example. "Inclusive fitness effects are likely at work here, though in ways that are evolutionarily novel," says Crespi.

Of course, as with other kinds of extreme behaviour, there are factors that aren't rooted in evolution. Many people who commit horrific acts grew up in abusive or otherwise detrimental environments, which can have neurological, psychological and genetic consequences. And some behaviours are down to random mutations. "Crazy mass killers are likely just that – insane – which is maladaptive like any other disease or major disorder," says Crespi.

Where does all this leave us with regards to the big question? Good and evil don't exist in any real sense. And there is a positive take-home message. The evolutionary pressures that can make humans violent can also make us extremely peaceful, says Martha Robbins, a primatologist at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. Our sense of morality can eliminate – or at least minimise – evil in society. **Rowan Hooper**

"Everything that can happen
does happen, only in
different universes"





DO WE HAVE FREE WILL?

DID I really just decide to have fish and chips for lunch?" Humans have been wrestling with such questions for millennia. Maybe not about the fish and chips, but about whether we are truly in control or whether some external agent – be that an omnipotent god or the laws of physics – predetermines the trajectory of our lives.

Unfortunately, there are no

easy answers. Who is the "I" who decided to have fish and chips? Your gut reaction might tell you that you are a conscious entity controlling your physical body. But that physical body includes the brain that generates your consciousness (see "What is consciousness?", page 29). There is no splitting the two.

We do know that any sense we have of being in control of

our actions is, to some extent, an illusion. In particular, neuroscientist Benjamin Libet showed in the 1980s that mechanisms within the brain initiate actions long before that brain's owner is aware of deciding to perform them.

It's a big extrapolation to claim all of our actions are outside our control. "Libet deals with the very short-term precursors of very simple actions," says Patrick Haggard, a neuroscientist at University College London. Then again, even longer-term decisions and actions are the result of specific brain processes. "I assume this is also deterministic," says Haggard (for a sociological and ethical discussion of free will see "What if we have no free will?", page 21).

For Nicholas Humphrey, emeritus professor of psychology at the London School of Economics, acknowledging that decisions have an involuntary, material cause in brain processes does not amount to denying free will. "On the contrary, I'm saying that I myself am the cause of it," he says. Humphrey calls his "I" an "embodied self": the sum of the thoughts, beliefs, desires, dispositions and so on within him. The embodied self might not be conscious of every action, but it determines them – sort of free will on autopilot.

A physicist might question that separation of personhood from other material parts of the universe. Biological material is nothing more than agglomerations of atoms and molecules that follow the laws of physics – and surely we can't claim to be in control of those. Vlatko Vedral, a physicist at the University of Oxford, thinks that to understand free will (or the lack of it) we need to better understand what makes the universe tick. "My guess is we will be able to

illuminate it more and more as we reduce more complex natural sciences, such as biology and neuroscience, to physics," he says.

If it is all down to physics, that doesn't mean everything is predetermined. Quantum physics, our most fundamental theory of how the building blocks of the universe behave, seems to say that a degree of randomness and uncertainty is built in to particle properties and movements – including those that make us up. Scale that up, and what happens in the universe can't be entirely determined from beginning to end, because you don't know what's going to happen at the quantum scale.

Quantum decisions

Unless, that is, you believe the many-worlds interpretation of quantum theory, which says that all this uncertainty is only because everything that can happen does happen, only in different universes. In this scenario, the universe really is predetermined. The only uncertainty lies in which pre-packaged universe you find your conscious self in: the one where you ordered fish and chips or the one where you didn't.

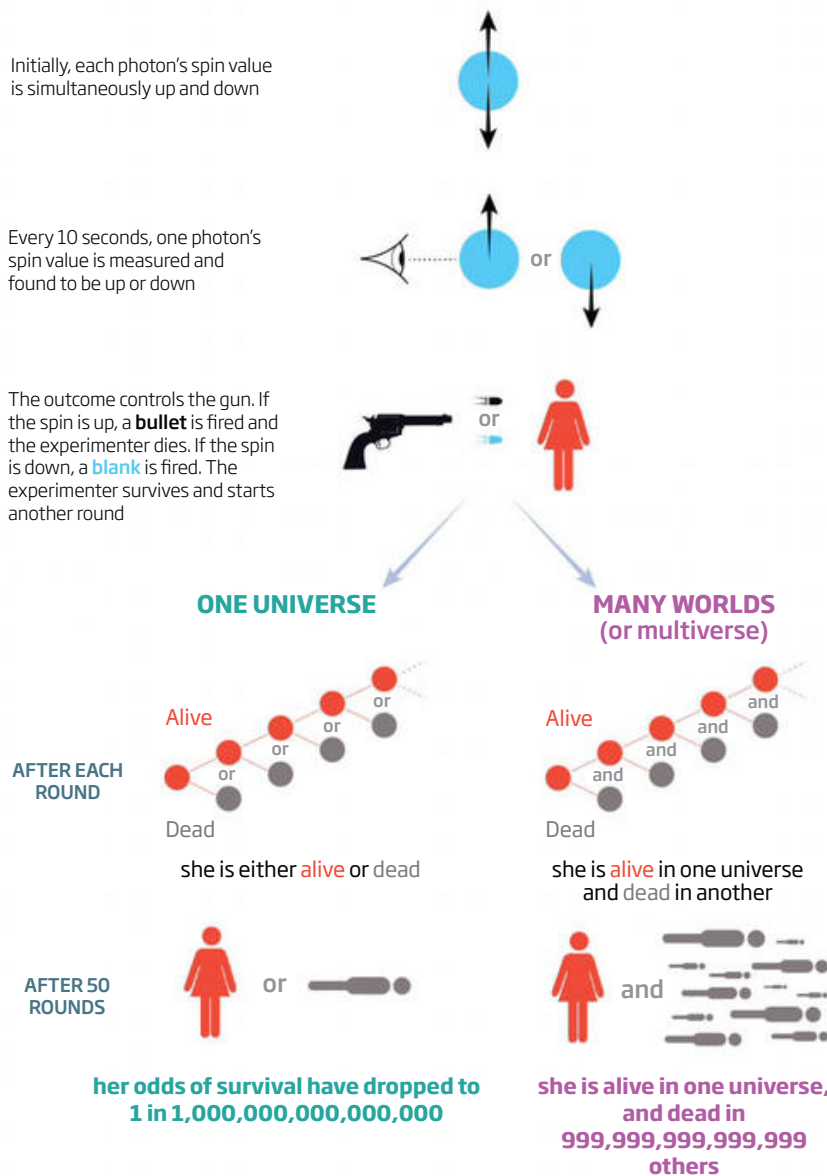
Or you can take it even further as some physicists do, notably Nobel laureate Gerard 't Hooft of the University of Utrecht in the Netherlands. He argues that the universe is superdeterministic – that something outside it sets everything in stone, including the outcome of experiments to test whether we have free will. To some people this amounts to a god. Vedral admits the possibility can't be discounted. "Because we are finite, and part of the universe, we would still perceive it as non-deterministic." There are some battles you just can't win. **Michael Brooks**

50 ways to test the multiverse

The many-worlds hypothesis says that the universe splits in two when we observe an object. By contrast, quantum theory says that two versions of a quantum object are equally likely until it is observed, at which point one disappears.

Which of these interpretations is correct has implications for the nature of reality (see "What is reality made of?", right) and free will (see "Do I have free will?", page 33). So can we test them? Possibly, but it would be unpleasant.

Quantum Russian roulette is a thought experiment developed by physicist Max Tegmark to test the many-worlds hypothesis. It begins with an experimenter, a gun and photons.



If the experimenter is alive after 50 rounds, she can assume that she is living in a multiverse



WHAT IS REALITY MADE OF?

EVERY age in history has its own ideas about what makes up the universe. "Questions about what kinds of things exist go all the way back to the earliest philosophical texts," says Jan Westerhoff, a philosopher at the University of Oxford.

For many ancient peoples, basic elements such as earth, air, wind and fire formed the

IS TIME AN ILLUSION?



WE ARE born. We die. We call the span that separates these events time. Its passage is perhaps the most fundamental feature of our human experience, yet we are incapable of saying exactly what it is. Worse – the laws of physics don't help. That time exists is undeniable, but the way we experience it makes no sense (see “The now delusion”, page 94).

“There’s an old joke about time – it’s nature’s way of keeping everything from happening at once,” says physics Nobel laureate Steven Weinberg of the University of Texas, Austin. To us mortals, time is the passage of the sun and seasons, the progressive wrinkling of our skin as we age – irreversible markers of a present that is moving forwards, and a future that is ineluctably becoming the past. Unlike space, time has a natural order. If A influences B, then B is always later in time. This is the central feature of time as we perceive it: as a flowing entity that orders our lives.

There’s one problem with this, says David Deutsch of the University of Oxford: it’s nonsensical. We see ourselves in a present that marches down an imaginary timeline at a set pace (see “Why do we move forwards in time?” page 50). The imagery implies the existence of some sort of universal ticking time setting the beat against which all else is measured. “But what is that other time?” says Deutsch. We’ve only succeeded in creating a new problem.

In Einstein’s relativity, our best large-scale theory of the universe, there isn’t even a single objective metronome tick. Time becomes folded up with space into a malleable, four-dimensional space-time, and its passage depends on how fast you are moving, or the

strength of the surrounding gravitational field. Yet of the four dimensions of space and time, time remains somehow special. “If I tell you what’s happening in a region of space like the solar system, then we can predict what will happen in that same space at a different time, but not what is happening at the same time in a different space,” says Deutsch.

Quantum mechanics, the other pillar of modern physics, reinforces this view of time as something apart, while producing a picture completely at odds with relativity. Here, there is an objective “god’s eye” time that allows you to see all events encapsulated in time, including the future, from outside it. But while all quantum-mechanical observables – things that can be calculated about reality – depend on it, time is not itself an observable, so cannot be calculated. It can’t even be reliably measured: the principle of quantum uncertainty makes it impossible to distinguish the order of two events that are very close in time. “It gets harder to prevent effect preceding cause,” says Weinberg.

So between quantum theory, relativity and our own aberrant perception of a flowing time, we’re left in a pickle. “All three conceptions are inherently problematic,” says Deutsch, “quite apart from conflicting with each other.”

One hope is that a brighter, shinier theory will unite quantum theory and relativity, and also illuminate time’s true nature, but such a theory is still a long way off. In the meantime, Deutsch thinks our best clue comes from calculations done by physicists Don Page and William Wootters more than three decades ago. They showed that pairs of quantum “entangled” particles, whose properties influence each other even at a distance, naturally evolve to provide anyone inside a universe with an illusion of time passing – while to anyone looking from outside the universe nothing would be happening at all.

Experiments in 2013 provided tentative support for this idea of time as an illusory emergent phenomenon. If true, it could begin to explain some of our difficulties. Just as we are bound by geometry to view Earth as flat even though it is curved, so we are not able to experience “real” time. “Our perception is on a very coarse-grained scale,” says Deutsch. “We don’t see the multiplicity of stuff joining up and being entangled.”

That’s still speculative, and far from a general physical theory of time. But perhaps we shouldn’t lose too much sleep over it. No amount of understanding time will change the truth about ours – that it is limited. Time to make the most of it. **Richard Webb**

essence of the cosmos. In the past century or so, we have concluded that matter is built from atoms, that atoms are constructed from a small set of elementary particles, and that those particles are fluctuations in a melee of quantum fields pervading empty space (see “Why is there something rather than nothing?”, p30).

So, job done – reality

explained? Not so fast, says Westerhoff. “You need to be absolutely clear about the sense of the word ‘reality’ – otherwise the discussion is going to be all over the place.” For a start, do only physical objects like earth or atoms count towards reality – or things like minds and consciousness, too?

Although the scope of our ➤

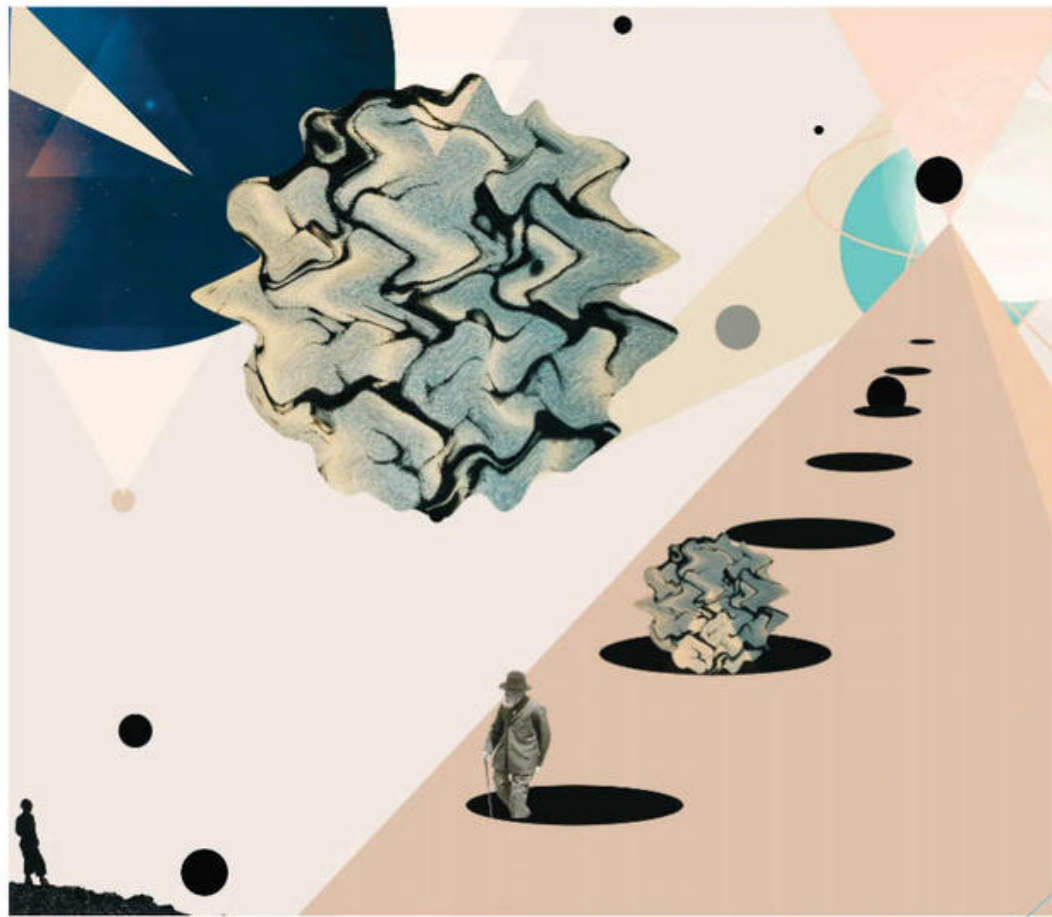
definition determines the complexity of the puzzle, physics should still supply the solution, says philosopher Tim Maudlin of New York University. Physics is about just two questions, he says: “what exists?” and “what does it do?”. “If you answer both of those questions, then I think you have answered the question ‘what is reality?’.”

If so, we’re still a country mile from a resolution. Modern physics supplies answers for only about 4 per cent of material reality – the other 96 per cent exists as mysterious “dark” matter and energy. Essential components of reality such as space and time also remain unexplained (see “Is time an illusion?”, page 35).

The problems are deep-rooted. Quantum theory is the best description of material reality devised, yet we cannot get our heads around what it says. It seems to imply all possible states of a quantum object are equally real until a measurement forces a single state to exist – a bizarre state of affairs pilloried by physicist Erwin Schrödinger in the 1930s, with his quantum cat that was simultaneously dead and alive until someone looked at it (see “Could we destroy the universe?”, page 89).

The questions that raises are legion. Why is one version of the cat chosen over the other, and what determines which one? What happens to the other version – does it simply cease to exist, or do both persist in parallel versions of reality? The mathematics of quantum theory, while providing a flawless description of the outcomes of measurements, is silent on these crucial questions. And so we hit a brick wall – or do we?

The other possibility is that



we are glimpsing something very profound. If the mathematical description is precise but the physical interpretation is messy, might mathematics be the only real thing? In this picture, you can forget matter and energy, whether conventional or dark. The most fundamental things are the 1s and 0s of information, and the universe is nothing but a gigantic data-processing machine. A star, for example, is not a nuclear fusion reactor building successively heavier atomic nuclei, but a computer processing information into more complex forms.

“What we perceive as the physical world is a kind of crystallisation of abstract

mathematical structures,” says Westerhoff. Follow this creed, and the ultimate theory of physical reality must come from the mathematical discipline of information theory, with space and time, particles and energy, forces and fields dropping out naturally from this magnum opus.

We then have to ask why our brains construct physical entities from the underlying numerical reality. An answer to that one, and indeed any true understanding of reality’s essence, may require understanding the prism that is consciousness, too (see “What is consciousness?”, page 29). Until then, we may remain like the prisoners in Plato’s allegory of the cave

who, unable to turn their heads to see objects casting shadows on the cave wall, believe that the shadows themselves are the true reality. Our age’s idea of what makes up the world may be no less flawed than those that came before. **Stuart Clark**



JOSEBA ETXABURU/REUTERS

CAN WE EVER KNOW IF GOD EXISTS?

IT COST more than \$13 billion and took 14 years, but eventually, as expected, God showed up. The joy and relief were immense. That was in 2012, and the evidence has only become stronger. Disbelief is no longer an option. God is real. Not the God of course, but Her particle, aka the Higgs boson.

If only proving the existence of God were that simple. Gallons of ink and blood have been spilled over this question but have largely got us nowhere. Belief in a god or several gods is a leap of faith. So is disbelief. The only coherent and rational position is agnosticism.

On the surface, the prospects for changing that seem remote. Demonstrating the existence of the Higgs boson – a material entity whose properties were established by particle physics – was one thing. How can you do the same for a supernatural being that is, among other things, everywhere and nowhere, immanent and transcendent, knowable and incomprehensible?

That has not stopped scientists and philosophers on both sides from having a go. For theists, one argument has been the intricate complexity of the natural world. Surely something as beautiful and functional as an eye or butterfly is irrefutable evidence of a creator? The superficially persuasive argument, later resurrected as intelligent design and its idea of irreducible complexity, turned out to be very refutable indeed. Evolution by natural selection, working over vast lengths of time, is all you need.

As science has progressed, such “evidential theism” has crumbled and some modern religious philosophers have retreated to a position known as reformed epistemology. They hold that God’s existence requires no justification or evidence. God just is, period.

To the scientifically minded that looks like a hopeless cop-out, and so evidential atheism has gained momentum. One avenue is the cognitive by-product hypothesis, which says that human brains are primed for religious belief because of, among others, the “hyperactive agency detection device” – a hair-trigger assumption that everything in our environment is caused by an often-invisible

agent. The evolved system would have given our ancestors an edge: divining the presence of an animal in the rustling branches of a bush meant they were better prepared to pounce or flee. Today, though, it means we are inclined to see an invisible hand in most if not all phenomena we can’t immediately explain.

Physicist Victor Stenger was one of evidential atheism’s greatest exponents. In 2007, he published *God: The failed hypothesis*, in which he pointed out that the Abrahamic God worshipped by billions of people either exists, or does not. If it does, there ought to be observable consequences.

Evidence of absence

Stenger (who died in 2014 and may now be repenting at leisure) went on to spell out a number of those consequences. For example, if God is the source of morality, non-religious people should be more immoral than religious ones. If God created the universe, we should see supernatural signatures in the laws of physics and cosmology. If God answers our prayers, prayers for the sick should work like medicine and clinical trials should show them to do so. None of these has ever been observed, said Stenger, and so we should revert to the null hypothesis: God does not exist.

According to Scott Aikin, a philosopher of religion at Vanderbilt University in Nashville, Tennessee, Stenger’s conclusion still stands. “The evidence points to the fact that God doesn’t exist,” he says. “I’m of the view that absence of evidence is evidence of absence.”

There are other reasons to reject the God hypothesis, he says, not least the many logical paradoxes it creates. Could an omniscient and omnipotent God create a secret that she doesn’t know or a stone that she could not lift? And then there is the paradox of worship: it requires complete submission to God’s will, yet we are said to be autonomous beings (see “Do we have free will?”, page 33).

There are many ways to wriggle out of evidential atheism’s arguments. One is “divine hiddenness”, which says that God will only reveal herself to people who really, really want to have a relationship with God, and then only after a struggle. If true, it is no wonder that atheists don’t see any evidence.

It doesn’t take much to see that there’s no arguing with this: like a conspiracy theory, it insulates itself from refutation. That places it outside the realm of science, which is where many believers locate God anyway. And probably for the best: if God belongs anywhere, that is where. **Graham Lawton**



SIX PRINCIPLES / SIX PRO

As Einstein once wrote, “The most incomprehensible thing about the universe is that it is and don’t know about how the cosmos ticks – starting with six basic principles that underlie

1

PRINCIPLES

THE SPEED OF LIGHT IS A CONSTANT

Nothing can exceed this cosmic speed limit

Back in the 1860s, James Clerk Maxwell was melding electricity and magnetism into one unified theory. But however he sliced the equations, they only made sense if light travelled through space at the same constant speed, regardless of the speed of its source.

This is odd. If someone fires a bullet from a moving car, to a bystander the bullet travels at the sum of its speed and the car’s speed. Yet when 20 years later US physicists Albert Michelson and Edward Morley were looking for the luminiferous ether, a medium supposed to carry light, they reached the same conclusion: however you look at it, the speed of light is a constant.

Not only that, it is the ultimate cosmic speed limit. No influence – not matter, not information, not gravity nor any other force – may travel faster than it. Reports of cosmic speed breakers, such as faster-than-light neutrinos announced in 2011, have always turned out to be wrong. Einstein raised the constant speed of light to a principle of nature, and began to rebuild physics around it – the starting point of his twin theories of relativity.



2

PRINCIPLES

THE EQUIVALENCE PRINCIPLE

Gravity and acceleration always look the same

In the 16th century, Galileo noticed that falling objects accelerated at the same rate regardless of their mass. A feather and a hammer dropped from the Leaning Tower of Pisa will hit the ground at the same time, once you discount air resistance. During the Apollo 15 lunar landing, astronaut David Scott confirmed that principle on the airless moon.

Newton showed that this could only be true if an odd coincidence held: inertial mass, which quantifies a body’s resistance to acceleration, must always equal gravitational mass, which quantifies a body’s response to gravity.

There is no obvious reason why this should be so, yet no experiment has ever prised these two quantities apart.

As with light’s constant speed, it was Einstein who declared this equivalence a principle of nature.



3

PRINC

THE COSMOLOGICAL PRINCIPLE

The universe is the same in all places and in all directions

A few decades before Galileo, Copernicus dared to suggest that Earth was not a special place in the cosmos.

A century or so later Newton in his great treatise *Principia* assumed that the solar system was embedded in a uniform space that extended vast distances in all directions.

These are the origins of what in modern cosmology has morphed into the cosmological principle: gaze out into the universe and everything is more or less the same everywhere and in whatever direction you look. Local clumps of matter exist in the form of solar systems, galaxies and clusters of galaxies, but on a big enough scale, everything averages out to uniformity.

It’s a simplification that makes the mathematics a lot easier when we’re trying to build a working model of the cosmos. But our limited view makes it difficult to say whether it truly is a universally valid principle. The discovery of ever-bigger structures, for example, 2013’s whopping 10 billion-light-years-wide arc of galaxies dubbed the Hercules-Corona Borealis Great Wall, is calling that into question.



BLEMS / SIX SOLUTIONS

comprehensible". Over the next eight pages we invite you to explore what we currently do our theories of physics on scales large and small. By Stuart Clark and Richard Webb

IPLES

4

PRINCIPLES

5

PRINCIPLES

6

QUANTISATION

Things come in bite-size chunks

The origin of quantum theory was, quite literally, a light-bulb moment.

In 1900, Max Planck was trying to describe mathematically the energy output of light bulbs, and so make better ones. Existing theories failed to match reality. After a few false starts, Planck found he could bridge the gap by making a radical assumption: the electromagnetic energy given out by a radiating body was emitted not continuously, but in indivisible packets.

Planck initially thought these "quanta" were a limitation of the theory, not a description of reality. But in 1905, Einstein showed that the way some metals expel electrons when light shines on them – the photoelectric effect – could also be explained by assuming that light is made of discrete particle-like quanta, which he called photons. This was just the beginning. As quantum theory developed, it became clear that not just energy, but many other properties such as electric charge and spin, come in units of a minimum size. Why that should be, no one knows.



UNCERTAINTY

There's a limit to how much any of us can know

If you kick a football, knowing where it is doesn't stop you knowing where it's going. Not so with a subatomic particle. The more precisely you know its position, the less precisely you know its momentum, and vice versa.

This is the quantum uncertainty principle, devised by Werner Heisenberg in the mid-1920s. It connects not just position and momentum, but energy and time and a whole host of other pairs of quantities. Uncertainty doesn't come from the accuracy of our measuring devices: it is apparently a fundamental limit on how much we can know about the world.

Uncertainty shapes our world in unsuspected ways. It allows particles to "tunnel" through otherwise insurmountable energy barriers to initiate nuclear fusion in the sun, for example. It also enables them to pop up out of a seemingly empty vacuum for short periods – an ability that's crucial for explaining how the quantum forces that shape reality operate.



WAVE-PARTICLE DUALITY

Quantum objects exist in many different guises at once

The discovery in the early 20th century that light comes divided into discrete, localised chunks – particles – created a puzzle. Light also interferes with itself, diffracts and otherwise acts as if it is a non-localised wave.

In 1924, Louis de Broglie proposed that this behaviour was universal and worked both ways: if wave-like light can act like a particle, electrons and other matter particles can also act like waves.

In this dual wave-particle picture, a quantum object exists in a wave-like "superposition" of all its possible positions or states, only settling in one state on measurement. Erwin Schrödinger lampooned this idea in his thought experiment about a cat that is simultaneously alive and dead.

But experiments since have made single particles as large as buckyballs – molecules made of 60 carbon atoms – diffract and interfere at two slits as if they were a wave, and superposition is one basis of the much-touted, enhanced information-processing power of future quantum computers.



From constant
speed of light

SPECIAL RELATIVITY

As Einstein worked out, the principle of a constant speed of light has some odd consequences. In everyday experience, two cars approaching each other at 100 kilometres an hour would collide at double that, 200 km/h. But imagine you're sitting in one of two spaceships approaching each other, each travelling at 90 per cent the speed of light, c . From the perspective of one, at what speed is the other approaching?

The exact figure doesn't matter* – but it can't be bigger than c . In Einstein's special theory of relativity of 1905, time and space warp to accommodate light's speed limit. Moving clocks tick slower and moving rulers appear shorter, so there is no one objective measure of time and space – and you really will age less in a speeding spacecraft. At our normal speeds, these warping effects are negligible, but close to light speed they become hugely significant, and ensure no object can ever cover a given space in a shorter time than light can.

**It's 99.4 per cent of the speed of light*

$$E=mc^2$$

This most famous equation of physics stems from special relativity, and says that mass is just a concentrated form of energy, connected by the constant speed of light. So bash particles together at very high energies, as in CERN's Large Hadron Collider, and you can create other, more massive particles – a path of discovery that eventually led to the standard model of particle physics.

THE COSMIC MICROWAVE BACKGROUND

Discovered by accident in 1964 as a background hiss in a gigantic telecoms receiver, this cool sea of radiation is now seen as clinching evidence of the big bang. The oldest light in the universe, it was sent on its way some 380,000 years after the big bang, when the cosmos had cooled enough for the first atoms to form, allowing photons to travel freely. Probes, most recently the European Space Agency's Planck mission, have mapped this light in detail, providing information on the universe's earliest years and its make-up today.

From the
equivalence
principle

From the
cosmological
principle

GENERAL RELATIVITY

Einstein's warped theory of gravity

If motion warps space and time (see "Special relativity", left), then so does acceleration – and gravity is a form of acceleration. That's the lesson of Einstein's magisterial general theory of relativity of 1916, which combines special relativity and the equivalence principle into our working theory of gravity. Massive objects bend space and time around them, making things seem to accelerate towards them. General relativity provides a framework to explain the large-scale workings of the universe, but a cosmological model requires further information: how matter is distributed.

GRAVITY

Gravity explains why we feel a downwards pull towards Earth and why Earth orbits the sun. Although dominant over cosmic scales and near very large masses like planets or stars, it's actually by far the weakest of the four known forces of nature – and the only one not explained by quantum theory.

GRAVITATIONAL WAVES

These ripples in space-time were the last unconfirmed prediction of general relativity until they were finally spotted in September 2015. The signal of two massive black holes spiralling together and merging was a triumph of painstaking, patient detective work by the Advanced LIGO experiment.

THE STANDARD MODEL OF COSMOLOGY

When Einstein first used general relativity to build a cosmic model, he followed the orthodoxy of the day and assumed the universe was static: neither expanding nor contracting. Observations in the 1920s, however, showed that distant galaxies are "redshifted" as if they are moving away from us. Others then used his theory, plus the simplifying cosmological principle that the universe's matter is uniformly distributed, to build models of an expanding universe. This was the beginning of today's standard cosmological model. It describes a universe that began in the hot, dense, infinitesimal pinprick of the big bang some 13.8 billion years ago – and contains a few surprises that we still find hard to explain.

To the problems

From
quantisation

From
uncertainty

From wave-
particle duality

QUANTUM MECHANICS

The theory of subatomic particles and forces

If general relativity is the theory of the universe at large, on small scales quantum mechanics calls the shots. Derived from the principles of quantisation, uncertainty and wave-particle duality, it is a peerless predictor of the workings of subatomic particles – although the principles behind it often remain counter-intuitive and mysterious. Like general relativity, quantum mechanics is just a framework. Before it can be applied to the workings of real particles that often move at close to the speed of light, it must be married in some way with special relativity.

ENTANGLEMENT

Einstein didn't think much of this consequence of quantum theory when he proposed it with two other physicists in 1935. The states of two once-correlated quantum particles can remain correlated, even when they are separated by a long distance.

Interfering with one appears to have a spontaneous effect on the other. Einstein dismissed this as “spooky action at a distance”, insisting that some unseen physical influence must regulate entanglement. Thus quantum mechanics must be incomplete.

Many experiments have since shown no trace of that physical influence. If it does exist, it must travel at least 10,000 times faster than light, in flagrant defiance of Einstein's own special relativity. The current distance record for entanglement stands at 143 kilometres between photons on two different Canary Islands – with plans to extend tests into outer space.

QUANTUM FIELD THEORIES

Mass and energy are interchangeable, so says special relativity. Particles can pop out of nowhere, says quantum theory. Quantum field theory marries those ideas to depict all particles as “excitations” in underlying fields. The British physicist Paul Dirac started the ball rolling in the late 1920s with his equation describing how relativistic electrons behave.

The Dirac equation had a sting in its tail: it predicted the existence of a particle identical to the electron in every way, apart from the opposite electric charge. The positron, the first antimatter particle, was duly discovered in cosmic rays a few years later. It was the first of a whole new menagerie of particles that theorists proposed as quantum field theories evolved – and that later popped up in reality.

ELECTROMAGNETIC FORCE

Transmitted by massless photons of light, this is the most familiar of the quantum forces, governing all electric and magnetic phenomena.

WEAK FORCE

The weak force governs nuclear processes such as radioactive beta decays that are crucial, for example, in how the sun burns its fuel. It is transmitted by massive particles known as W and Z bosons.

STRONG FORCE

Transmitted by bosons called gluons, this strong, very short-range force binds quarks together to make particles such as protons and neutrons.

THE HIGGS BOSON

Mass is the most solid property of matter, and the mass of a fundamental particle is determined by its degree of interaction with the Higgs boson. According to a theory first proposed in 1964, the molasses-like field associated with the Higgs provides a drag that varies according to particle type.

THE STANDARD MODEL OF PARTICLE PHYSICS

The product of many decades of theoretical work, meticulously confirmed by experiment, the standard model of particle physics covers the workings of three of the four forces of nature. It describes the interactions of force-carrying boson particles with matter-making fermions, and two quantum field theories lie at its heart. Quantum electrodynamics (QED) is the unified “electroweak” theory of electromagnetism and the weak nuclear force. Quantum chromodynamics (QCD) is the theory of the strong nuclear force. The crowning glory of the standard model came in 2012, with the discovery of the Higgs boson, predicted almost five decades earlier.

This leaves a theory that is complete – yet also strangely incomplete.

To the problems

To the problems

The standard models of cosmology and particle physics provide powerful predictions for the workings of nature on their respective scales. But where they meet, they produce contradictory answers – and other problems they create mean they provide a far from complete picture

From the standard model of cosmology

1

PROBLEMS

DARK MATTER

Galaxies rotate too quickly for their visible matter

Earth whirls around the sun at a speed determined by its distance, the sun's mass and gravity's strength, which is a universal constant of nature. You don't need general relativity to work that out: Newton's old-school gravitation will do. The same law should apply to distant galaxies swirling around their common centre of mass.

In the 1930s, however, the astronomer Fritz Zwicky discovered that the outer parts of the Coma galactic cluster were rotating far faster than the cluster's estimated mass allowed. In the 1970s, Vera Rubin confirmed the huge mismatch in a clutch of spiral galaxies similar to the Milky Way. She estimated they must contain about six parts of invisible matter for every one part of visible matter.

This "dark matter" must interact gravitationally to produce the motion, but hardly at all through the other forces of nature. The standard model of particle physics provides no particle that fits the bill, and efforts to detect dark matter particles beyond the standard model, or manufacture them in high-energy particle collisions, have so far come to naught. Something is missing.

2

PROBLEMS

DARK ENERGY

The universe is flying apart faster and faster

In the late 1990s, two groups studying far-off supernovae discovered that these stellar explosions were consistently fainter than expected. Their conclusion: the space their light had travelled through to get to us had stretched more than expected, so the supernovae were further away than supposed.

Dark energy is the name for whatever is causing this accelerating expansion. It dominates the cosmos, making up some 68 per cent of everything there is. But what is it? Perhaps a vacuum energy of the sort that quantum particles might create by popping in and out of free space. This would be a resurrection of the cosmological constant that Einstein introduced into the equations of general relativity, and then dropped. Or perhaps dark energy is a "quintessence", an as yet undiscovered fifth force of nature.

Both identities have their problems, and there could be another way out. A universe with a variable density of matter would expand at different rates in different places, possibly producing an illusion of accelerated expansion. So if we drop the cosmological principle we might possibly get rid of dark energy, too.

3

PROB

INFLATION

Faster-than-light expansion spawns many other universes

Range your eye across the cosmos, and a couple of features are hard to explain. It is darn near geometrically "flat", and even far-off bits all have almost the same temperature.

Cosmic inflation solves these problems at a stroke. In its earliest instants, the universe expanded faster than light (light's speed limit only applies to things within the universe). That ironed out wrinkles in its early chaotic self and meant that even now far-flung parts were once in close contact, so could swap heat.

In 2014, researchers claimed to have seen ripples from inflation imprinted on the cosmic microwave background. But this proved mistaken, and it's not clear what would have made the early universe inflate anyway. Worse, inflation is very difficult to stop, creating a multiverse of causally disconnected universes that eternally bud off from one another.

One way out might be to weaken the constant speed of light. If the speed of light were faster in the early universe, that would also explain the temperature problem. Perhaps light is still slowing now, just at a rate that is imperceptible even to our most sensitive detectors.

Reconsider the cosmological principle – return to principle 3

Reconsider the constant speed of light – return to principle 1

NEUTRINOS

Could neutrinos be dark matter? The standard model of particle physics says these elusive particles have no mass, but experiments now say they do have a small one – the only direct contradiction of a standard model prediction so far. But the extra mass seems unlikely to be enough to explain dark matter, unless as-yet undiscovered new varieties of "sterile" neutrino exist. Recent results from the European Space Agency's Planck satellite and the IceCube Neutrino Observatory in Antarctica seem to discount that.

THE COSMOLOGICAL CONSTANT

When Einstein created his static universe model (see "General relativity", page 40), he added an extra term in the equations of general relativity to counteract gravity's pull. He later called this cosmological constant his "greatest blunder". Tweaked to represent a quantum energy of free space, it might explain dark energy – but quantum theory supplies a huge 10^{120} times as much as is needed to set the universe speeding on its way. This is perhaps the most glaring numerical mismatch in all of physics.

To the solutions

From the standard
model of particle physics

From
entanglement

LEMS

4

PROBLEMS

5

PROBLEMS

6

FORCE UNIFICATION

*Our theories of reality
don't get along*

The standard model of particle physics covers three forces of nature, but doesn't unify the electroweak and strong theories neatly. Gravity, meanwhile, stands apart as the only force we can't describe with quantum theory. Any effort to make it quantum – to describe it through the exchange of particles called gravitons, rather than through general relativity's space-time warpings – is ripped apart by uncontrollable infinities that render all calculations meaningless.

When subatomic particles interact, gravity is generally so weak that it can safely be ignored. But in some realms, the two must come together: in black holes, for example, or in describing the universe's tiny origins in the big bang. Without a quantum theory of gravity – a first step to a unifying theory of everything – science faces an impenetrable barrier to ultimate enlightenment.

Just by the by, any theory of quantum gravity will require breaking the link between gravitational and inertial mass embodied by the equivalence principle – undermining a foundation stone of modern physics.

Reconsider the
equivalence principle –
return to principle 2

BLACK HOLES

Black holes are super-dense objects that swallow everything, including light, that strays too near. They come in different sizes: supermassive black holes lurk at the heart of most galaxies, and stellar-mass ones form when spent stars collapse in on themselves. Predicted by general relativity, black holes are also places where gravity is so strong that it can no longer be neglected on quantum theory's small scales – so we currently have no understanding of what happens at the edge of a black hole or inside one.

FINE-TUNING

*We can't explain the numbers
that rule the universe*

The standard model of particle physics is highly effective, but incomplete. It doesn't fully explain the different strengths of weak, strong and electromagnetic forces, for example, or the masses of the particles it introduces. These quantities have to be measured experimentally and tacked on to the theory. Were any of them to have even marginally different values, the universe would look very different. The Higgs boson's mass, for example, is just about the smallest it can be without the universe's matter becoming unstable. Similar "fine-tuning" problems bedevil cosmology. Why does the amount of dark energy and dark matter in the universe seem so finely balanced as to allow galaxies to form? Why is the carbon atom structured so precisely as to allow enough carbon for life to exist in the universe? And perhaps the most finely balanced of all: why does the cosmos have lots of matter, and no antimatter?

To the solutions

MEASUREMENT

*Do we inadvertently control
everything that happens?*

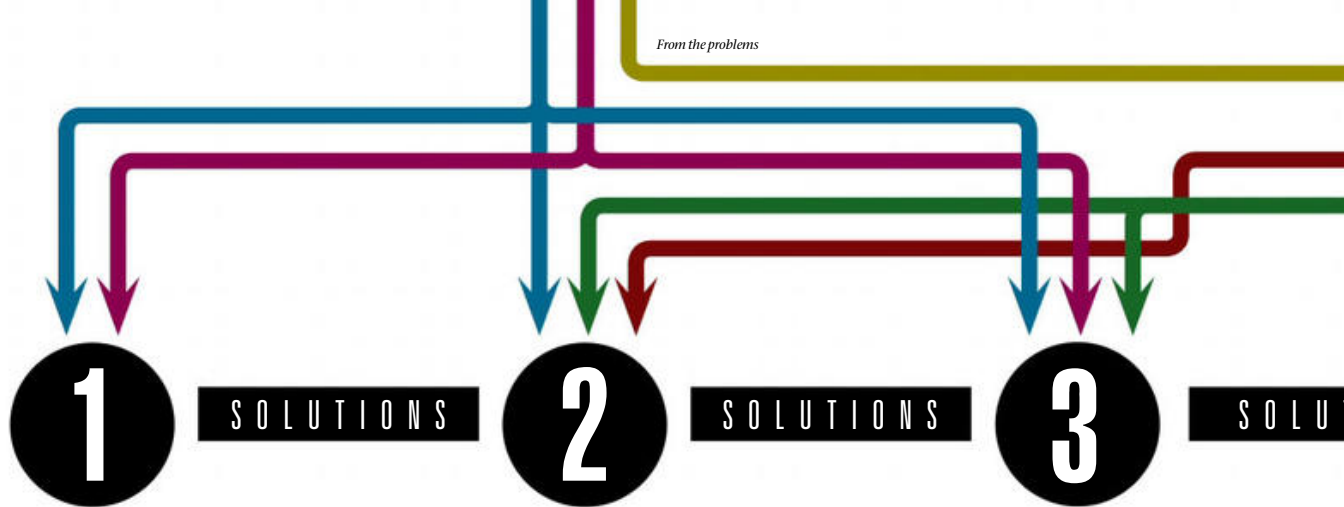
Features such as wave-particle duality and entanglement highlight a mystery at the heart of quantum physics. Our decision to measure quantum objects seems to change their nature, forcing them to "collapse" and adopt definite states. So are we co-conspirators in creating reality? If so, what does measuring a quantum object do to it, if anything?

One daring suggestion is the "many worlds" hypothesis, that the universe splits into a multiverse of possibilities every time we measure something. Or perhaps collapse is a preprogrammed, random feature of the quantum world, a principle just as central as wave-particle duality or uncertainty. Or perhaps, as Einstein believed, there's something fundamentally wrong in how we see quantum theory – in which case we need to review all the principles that underlie it.

Reconsider the basis of
quantum theory – return
to principles 4, 5 and 6

ANTIMATTER

Antimatter exists. Unwittingly predicted by Paul Dirac in 1928 (see "Quantum field theories", page 41), it was discovered in cosmic rays a little later. The mystery is rather why there is so little of it – or indeed anything at all. The standard model says matter and antimatter should have formed in equal quantities in the big bang, "annihilating" in a puff of light shortly after. Some currently inexplicable tiny imbalance caused matter to win out – allowing our universe of stars and galaxies to come to be.



MODIFIED GRAVITY

Our theories of gravity have only ever been tested on small scales

General relativity is a hugely accurate theory of gravity – as far as we can tell. But could modifying gravity perhaps exorcise some cosmic demons?

General relativity's predictions of the movements of probes and planets are accurate up to the scale of the solar system, and the recent discovery of gravitational waves (see page 40) indicates they are also spot-on about what happens when two orbiting black holes merge. But by cosmic standards, these systems have a lot of mass crammed into a relatively small space. What happens to gravity in environments where its strength is weaker?

A tweaked version of gravity called modified Newtonian dynamics (MOND) might describe the anomalous galactic rotations taken to be evidence for **DARK MATTER**, but there is as yet no theory for how this modification might come about. The DGP gravity hypothesis, meanwhile, named after the initials of its originators, suggests that gravity can leak out from our 4D space-time into a higher-dimensional "bulk", progressively weakening its effect over time and so producing the illusion of **DARK ENERGY**. We're yet to find any experimental evidence to back up this hypothesis, however.

SUPERSYMMETRY

More particles can explain why the universe is as it is

Supersymmetry, or SUSY to its friends, is the Swiss army knife of particle theories: it has a tool for everything. It works by suggesting that for every matter-making fermion in the standard model there is a force-carrying boson, and vice versa.

Double the particles means more than double the fun. Supersymmetry can solve **FINE-TUNING** problems such as the strangely low mass of the Higgs boson: interactions with "superpartner" particles rein it in to just the observed level.

Calculations done in the 1980s showed that if you assumed supersymmetry existed and extrapolated the strength of electromagnetism and the weak and strong forces back into the early universe, they could be made to **UNIFY INTO ONE SUPERFORCE** with stunning accuracy. The icing on the cake was that the lightest superpartner, the neutralino, supplied a ready-made identity for **DARK MATTER**.

Too good to be true? Probably. If supersymmetric particles exist, they should have been created at CERN's Large Hadron Collider by now. But aside from the odd exciting blip that subsequently went away, there's been no sign. Perhaps the superpartners are heavier than we thought, or perhaps we just haven't teased their existence from the data yet. But increasingly, particle physicists are facing an uncomfortable thought: nature might not have supplied as neat an answer as supersymmetry.

FIFTH FORCE

Could a quintessence banish cosmic ghosts?

Gravity, electromagnetism, the weak force and the strong force... four seems an arbitrary number of fundamental forces.

Why not more?

The most likely fifth force is a weak, long-distance force, a bit like gravity, that would probably interact with it. It might cancel a little of it and explain why the universe's expansion rate is accelerating, mimicking **DARK ENERGY**. Or it could add to gravity to explain the additional pull usually attributed to **DARK MATTER**.

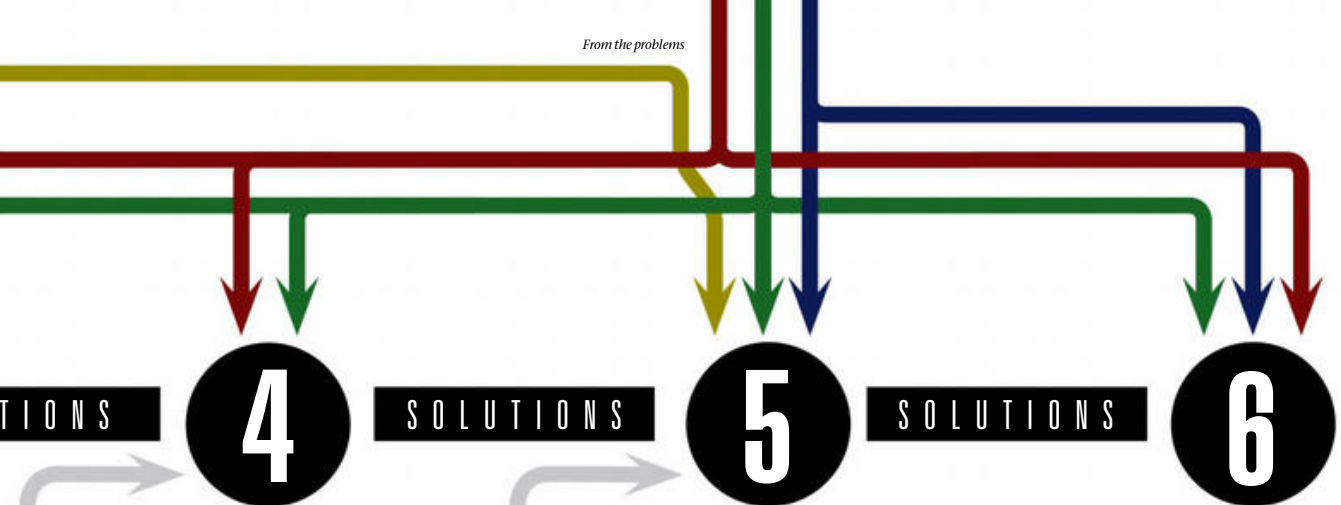
Such a fifth force would have to be cunningly disguised to explain why we don't feel it. One suggestion is that the large amount of mass in and around the solar system shields us from its effects. That also makes it a very hard idea to test.

Fifth forces with attendant quantum particles are also sometimes proposed to solve problems such as **FINE-TUNING** in particle physics, but there seems precious little evidence for new forces on this scale.

The occasional anomaly does keep physicists hoping, however: most recently, aberrations in the expected decay rate of radioactive beryllium nuclei have been touted as evidence of a whole new "dark sector" of particles and forces.

So there we are – or are we?

Our understanding of the universe has been completely rewritten in the past century – and is likely to be rewritten again. The ideas on this page represent possible ways forward, but in all probability progress will only come through some idea not yet even dreamed of.



STRING THEORIES

An ultimate theory must subsume quantum theory and relativity

Many physicists' dreams, including Einstein's, have been dashed in attempts to formulate a **UNIFYING THEORY** of all of nature's phenomena.

In the past few decades, a popular route to a theory of everything has emerged: string theory, and in particular a variant known as M-theory. In M-theory, matter is made not of pointlike particles as in the standard model, but of one-dimensional vibrating strings living in a universe with 11 space-time dimensions. These strings vibrate in different ways to create various elementary particles – even gravitons to carry a quantised gravitational force.

M-theory could solve **FINE-TUNING** and implicitly includes **SUPERSYMMETRY**. Its extra dimensions are curled up and tiny, explaining why we are not aware of them. Breakthroughs such as the discovery in 1995 of a way to link a theory with gravity in five dimensions with a purely quantum theory in four seemed to indicate it was the right way to unify forces and theories.

But advances similar to this "AdS/CFT correspondence" are yet to be made for space-times more like that of our universe, and string theory has yet to make a single testable prediction. Most perturbably, it seems to predict the existence of a multiverse of anything up to 10^{500} different universes (see right).

All that has led some to question whether string theory counts as science. Rival approaches do pop up from time to time. But all these theories are far from a theory of everything as most people would understand it: one that can also explain, for example, how properties such as consciousness "emerge" from the workings of inanimate matter.

THE MULTIVERSE

The universe is as it is – because every other universe is out there too

Many roads lead to the multiverse. **STRING THEORY** needs it. **INFLATION** creates it. In the many-worlds solution to the **MEASUREMENT** problem of quantum mechanics, we are constantly, unwittingly making parallel universes.

The first difficulty is that these multiverses are probably all different. The second is how you get convincing evidence for the existence of any of them.

But multiverses are in general both a blessing and a curse. The string theory or inflationary multiverse, for example, can solve problems like **FINE-TUNING**: other universes exist where all other possible configurations of matter exist, and our configuration just happens to be one of those where conditions were ripe for sentient, questioning beings to evolve. But such "anthropic" reasoning absolves us of the responsibility of asking that most probing of questions, "why?". It may be the best we can do, but by allowing every possibility besides the one you're probing to play out somewhere in the multiverse, science robs itself of its predictive power.

INFORMATION

Energy and matter don't matter – information is where it's at

When attempting to **UNIFY GENERAL RELATIVITY AND QUANTUM THEORY**, it's generally assumed that general relativity is at fault. It is, after all, a classical field theory of the sort that shinier quantum theories have otherwise nudged aside.

But as long as aspects of quantum theory such as the **MEASUREMENT** problem remain largely inexplicable, there's always the chance it is the wrong 'un, or just an approximation to some deeper theory.

What's truly pulling the strings of entanglement, for example? The world embodied by quantum theory is not the most entangled world out there – other, even weirder worlds exist in theory that have even greater degrees of correlation.

Why this entangled, and not more?

That might be another **FINE-TUNING** issue. But entanglement does seem to be at the root of many mysteries, and there are recent hints that it could be the warp and weft that holds space and time together. In that case, what is entanglement? The best we can say is that it's some sort of collective information shared between particles.

That highlights a common theme in much cutting-edge physics: that understanding space-time, and the route to a more unified picture of nature generally, lies in treating information – not matter and energy – as the most fundamental thing in the universe and understanding better how it works.

Perhaps looking at the universe through information-tinted spectacles will open us up to blindingly obvious solutions that make the problems we encounter today melt away. ■

WHAT CAME BEFORE THE *BIG BANG?* AND OTHER QUESTIONS PHYSICS CAN'T ANSWER... YET

Physicists ponder some of the deepest questions in nature, from the origins of the universe to the mysteries of matter. But they are far from having all the answers.

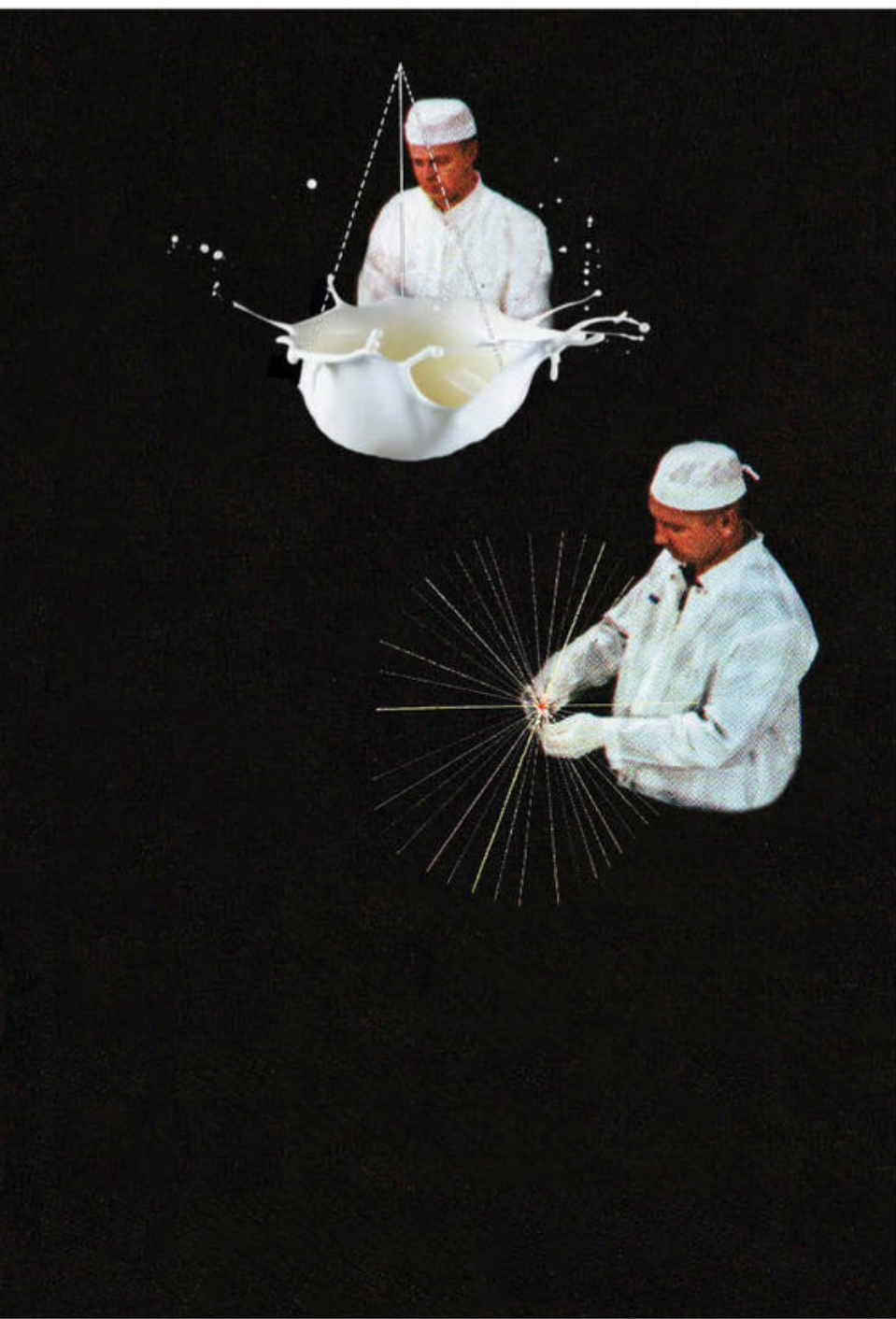
From why we travel forwards in time to how bicycles travel forwards at all, here is a collection of questions great and small that continue to stump our finest minds



MATTHEW RICHARDSON

WHAT CAME BEFORE THE BIG BANG?

PAUSE. Rewind. Suddenly the outward rush of 200 billion galaxies slips into reverse. Instead of expanding at pace, the universe is now imploding like a deflating balloon: faster and faster, smaller and smaller, everything hurtling together until the entire cosmos is squeezed into an inconceivably hot, dense pinprick. Then pshhht! The screen goes dead.



According to the big bang theory – our best explanation for why space is expanding – everything exploded from nothing about 13.8 billion years ago. Cosmologists have been able to wind things back to within a tiny fraction of a second of this moment. But now they're stuck.

The trouble is, our understanding of space-time, and gravity in

particular, is built from Einstein's equations of general relativity, whereas the extreme conditions of the very early universe can only be described by quantum mechanics. No one knows how to reconcile the two to take us further back. "The rules we have simply don't work in that regime," says Carlo Contaldi at Imperial College London. "Nothing makes sense any more."

That's a problem for our origin story. Did time begin with the big bang? Or was there an epoch before it?

Some insist that if we rewind the universe far enough, time just stops. But Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, is having none of it.

"It's a cute idea but there's not much evidence for it," he says. In fact, Smolin wants to see the idea that the universe has a starting point dropped entirely. We can only hope to explain why our universe is the way it is, he says, if there was something before the big bang. It's about cause and effect; to arrive at satisfying explanations for why things are as they are, we draw on previous events that led to the conditions we see.

One possibility is that instead of a bang, there was a bounce. In this scenario, rewinding our universe would not take us back to a point containing infinite mass in an infinitely small space. Instead it would take us through the unimaginably hot, dense beginning of our universe and out the other side into the unimaginably hot, dense ending of a previous universe.

Acknowledging that something came before the big bang would open the door to explanations of how the universe came to be just right for life. Otherwise we either have to accept that our perfectly crafted universe was just a fluke or that it is one of an infinite number of universes, most of which look very different, and we only think of it as special because we're in it.

Or perhaps our bang was one of many. Some think our universe popped into existence as a bubble in a frothing sea of universes. This idea gives our universe a beginning but introduces an everlasting multiverse.

Can we ever really know? Smolin thinks we could soon see clues in the cosmic microwave background – radiation given off by the early universe. It's possible that ripples in space-time known as gravitational waves might also survive a bounce.

Contaldi is not holding his breath. We need a working theory of quantum gravity and a new understanding of time, he says. Without that, "I don't think we have the tools to even pose the question properly."

Douglas Heaven

HOW DO BICYCLES STAY UPRIGHT?

IN 2011, an international team of bi-pedal enthusiasts dropped the bombshell that, despite 150 years of analysis, no one knows how a bicycle stays upright. Across the world, riders dismounted and stared at their bikes in disbelief. What they had been doing for years was a feat inexplicable by science.

Well, sort of. “What we don’t know are the simple, necessary or sufficient conditions for a bicycle to be self-stable,” says Andy Ruina, an engineer at Cornell University in Ithaca, New York.

We have relied on trial-and-error engineering to construct stable bikes that aren’t prone to toppling while in motion. Explaining how they work mathematically requires around 25 variables, such as the angle of the front forks relative to the road, weight distribution – important for balancing humans – and wheel size.

Before 2011, researchers had reduced this profusion to two things. One was the size of the “trail”, the distance between where the front wheel touches the road and where a straight line through the forks would meet the ground. The other was the gyroscopic restoring force that acts on a spinning wheel to keep it upright.

Ruina and his colleagues, including Arend Schwab of the Delft University of Technology in the Netherlands and Jim

Papadopoulos, now at Northeastern University in Boston, not only revisited this mathematics but also skewed the trail and gyroscopic forces in prototype bikes to make them technically unrideable. To everyone’s surprise, the bikes were still stable.

The researchers haven’t been resting on their saddles since. In 2014 Ruina unveiled a “bricycle”, a cross between a bicycle and a tricycle with spring-loaded stabilising wheels that can be adjusted to vary the rider’s perception of contact with the ground. By studying the influence this has on how the rider steers and remains stable, he hopes to gain new insights that might lead to more easily controllable bicycles.

It’s still an uphill struggle. “I think the real understanding of bikes requires a mix of what we did, plus some kind of brain science,” says Papadopoulos. Human riders act in extremely complex yet intuitive ways to keep a bike balanced and on track. At very low speeds, for example, we recognise that the handlebars become useless for steering, and instead direct the bike by wobbling our knees.

Why? “We don’t know,” says Schwab. Yet another bike-based mystery that could be around long after we’ve worked out the origins of the universe.

Michael Brooks



MATTHEW RICHARDSON

WHERE DOES QUANTUM WEIRDNESS END?

WE DO not find, at breakfast, that the milk is simultaneously poured onto our cornflakes and not," says Andrew Briggs, a physicist at the University of Oxford. Nor can you be in two places at the same time, no matter how hard you try. None of which is even remotely surprising. Until, that is, you consider that the laws of quantum mechanics insist that subatomic particles such as electrons routinely pull off such a feat.

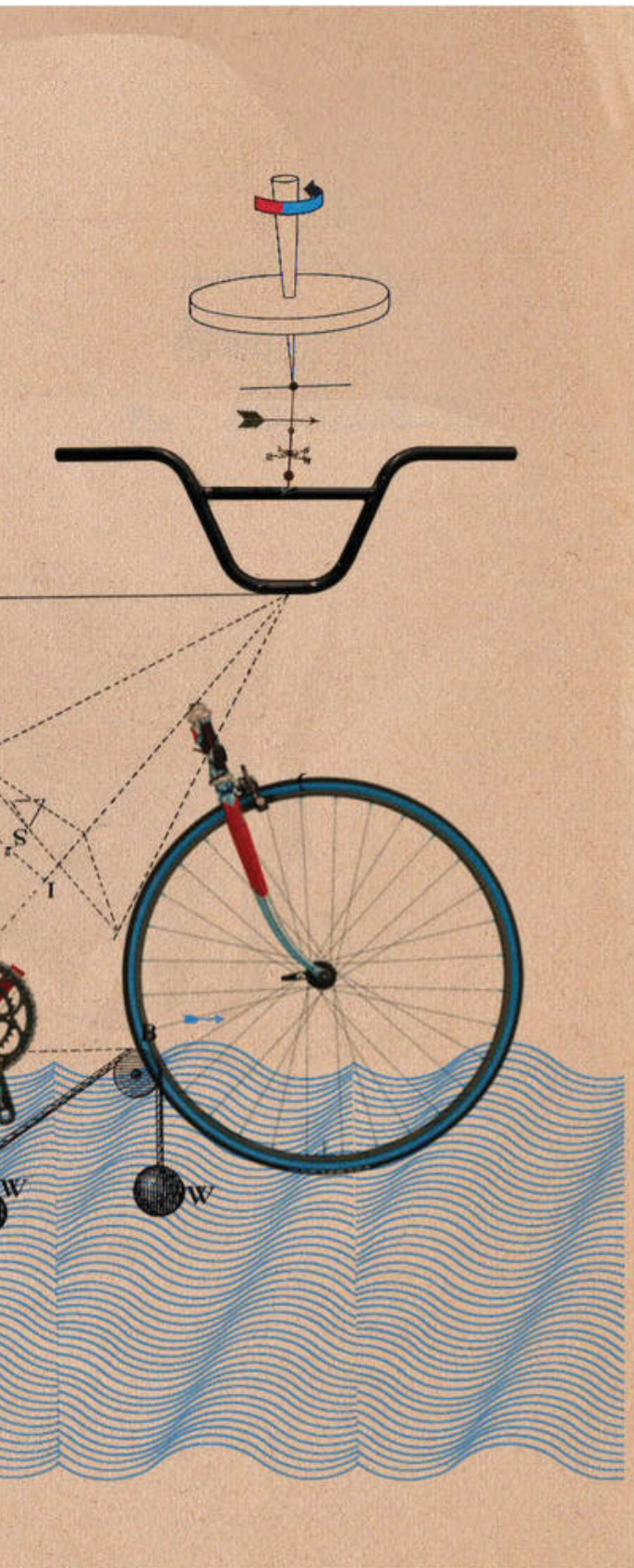
So if electrons can pop up in multiple places at once, why can't milk and humans – essentially collections of fundamental particles – do the same?

Here we have to start small. This particular brand of quantum weirdness is best illustrated by the double-slit experiment, where you fire a beam of electrons, one after another, at a screen containing two slits. You would expect the electrons to pass through one slit and hit the detector placed behind the screen at a single point every time. But reality isn't always that straightforward.

When researchers don't keep track of each electron's path, the beam passes through both slits simultaneously in the same way as a light wave, creating a pattern of bright and dark stripes on the detector that is characteristic of two overlapping wavefronts. So electrons can exist as both waves and particles at the same time – a phenomenon known as wave-particle duality.

As if that wasn't weird enough, when researchers monitor one of the slits, the interference pattern disappears. Electrons suddenly abandon their wave-like behaviour, preferring to travel through one slit and produce a single spot on the detector.

Physicists explain this by invoking the wave function, a mathematical widget that describes the probability of finding a quantum object in a particular state or location at any given time. When the particle is measured or disturbed in some way, its wave function collapses from a



superposition of many states into a single state and a definite position.

This collapse can be triggered by any interaction of a quantum object with its environment – a rogue vibration, for example, or a heat fluctuation. That leads us to an unsettling conclusion. Isolate a molecule even hundreds of thousands of times the size of an electron

“As Schrödinger said, it is absurd to say a cat can be both dead and alive at the same time”

sufficiently from its environment, and there's a chance it might still be existing in its uncollapsed quantum state. Indeed, researchers have now spotted improbably large objects – including tiny resonating strips of metal visible to the naked eye – existing in two states at once.

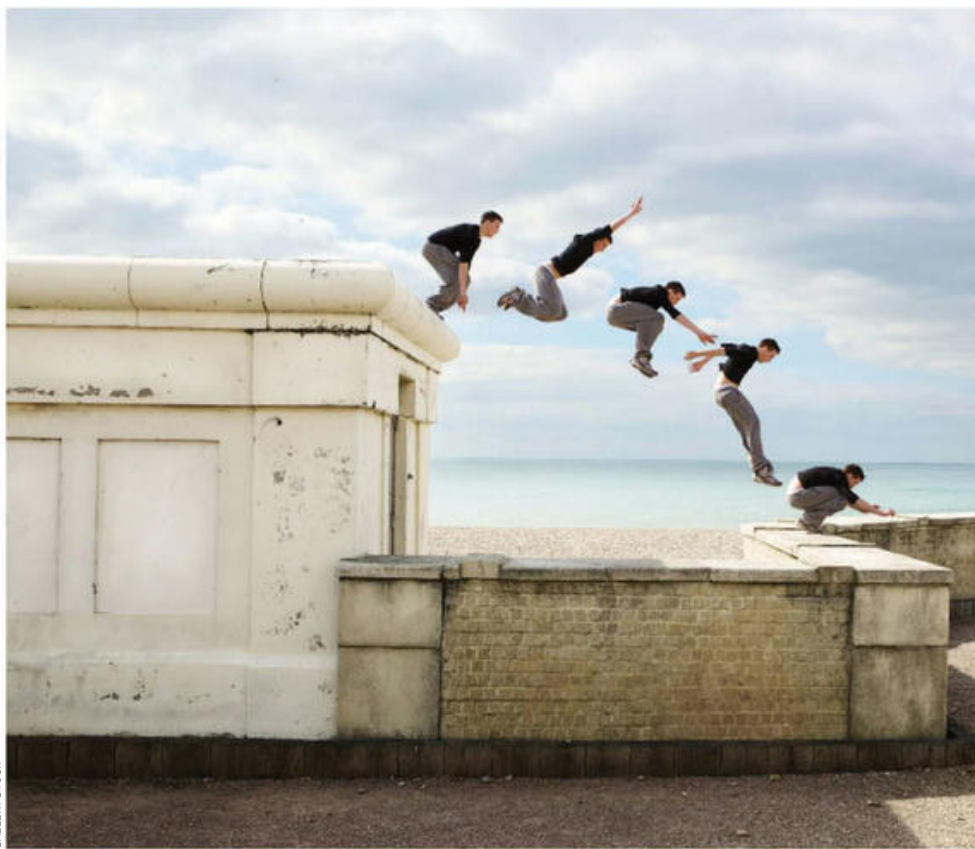
Even so, it's pretty clear that once something gets large enough, it throws off its quantum properties. As Erwin Schrödinger noted, it is absurd to say a cat can be both dead and alive. So how large can quantum weirdness go?

“Some physicists would say the size limit depends on the size of your chequebook,” says Briggs. With a sufficiently sophisticated experiment, he argues, researchers could screen out disturbances from the environment to show ever larger objects obeying quantum rules. Together with colleagues at Oxford, Briggs is testing the limits of quantum behaviour more rigorously than any experiment to date. The challenge is to find ways to place bigger things in fuzzy quantum states that are less sensitive to outside influences.

But Briggs does not expect to solve the conundrum any time soon. That's partly down to the difficulty of defining a “system” in quantum mechanics. Strictly speaking, anyone or anything observing quantum interference becomes part of the system, making it tough to draw conclusions about the size at which quantum effects vanish.

“You can always argue that you, the observer, are in superposition too,” says Briggs.

Joshua Howgego



GALLERY STOCK

WHY DO WE MOVE FORWARDS IN TIME?

THERE is a reason we say time goes by: it seems to flow. No matter how still we stand in space, we move inexorably through time, dragged as if in a current. As we do, events pass steadily from the future, via the present, to the past. Isaac Newton saw this as a fundamental truth. “All motions may be accelerated and retarded, but the flowing of absolute time is not liable to any change,” he wrote.

So how does time flow, and why always in the same direction (see “The now delusion”, page 94)? Many physicists will tell you that's a silly question. “The idea that time can in some meaningful sense be said to flow,

it's just a non-starter,” says Huw Price, a philosopher at the University of Cambridge (see “Is time an illusion?”, page 35).

For time to flow, it must do so at some speed. But speed is measured as a change over time. So how fast does time flow? George Ellis, a cosmologist from the University of Cape Town, South Africa, has an answer: “One second per second.” Price says that's meaningless. Even if time were standing still, it could be said that for every second that passes, 1 second passes. Indeed, if that's a measure of flow, we could say that space flows: it passes at one metre per metre.

Ellis is up against one of the most successful theories in physics: special relativity. It revealed that there's no such thing as objective simultaneity. Although you might have seen three things happen in a particular order – A, then B, then C – someone moving at a different velocity could have seen it a different way – C, then B, then A. In other words, without simultaneity



there is no way of specifying what things happened “now”. And if not “now”, what is moving through time?

Rescuing an objective “now” is a daunting task. But Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, has given it a go by tweaking relativity. He argues that we can rewrite physics in a way that includes “now” if we sacrifice some of our objective notions of space.

Most physicists aren’t having it. The general consensus is that time is more or less just like space – an immutable dimension, stretched out through a four-dimensional “block universe”.

“Every moment in that universe has a past, present and future,” says Sean Carroll at the California Institute of Technology in Pasadena. “A person is described as a history of moments, and those moments all have a feeling they’re moving from the past to the future.” That doesn’t answer the question so much as shift it. If time does not flow, what makes us think it does?

Michael Slezak

WHY DOES SPACE HAVE THREE DIMENSIONS?

AH, BUT does it? For anyone versed in modern theoretical physics, that’s not such a silly question. “I don’t know any mathematical reason why three-dimensional space is more consistent than any other number,” says Leonard Susskind of Stanford University in California.

Susskind is one of the founders of string theory, which is our best stab yet at a unified understanding of physics – and perhaps the best-known model in which extra dimensions are found. One of string theory’s peculiar features is that when applied to fewer than nine spatial dimensions, the mathematics goes wild, predicting violent fluctuations that rip apart the very fabric of the universe.

But extra dimensions do more than just save string theory’s blushes. In a wider set of theories, gravity leaking into a higher space could explain why in our three dimensions it is so weak compared with the other fundamental forces, and why the expansion of the universe is apparently accelerating.

So perhaps the question becomes: why does space have three *visible* dimensions?

One idea from string theory is that the universe started out as an infinitesimally small 9D ball of string, but only three strands unfurled in its subsequent headlong expansion, leaving the others tucked up tightly in every pixel of our 3D space. Or perhaps our 3D universe exists on one of many “branes”, membrane-like entities that float around in a larger, higher-dimensional space.

Lisa Randall of Harvard University and Andreas Karch of the University of Washington in Seattle have shown that branes colliding in such a space would tend to form 3D branes – an explanation of sorts for why we see a universe with three dimensions. If large other dimensions do exist,

particles escaping into them might take energy from those we see. CERN’s Large Hadron Collider has been looking for the signatures of missing energy – so far without success.

Such failures rile Carlo Rovelli of the University of Aix-Marseille in France. “The idea that space could have more than three dimensions was proposed more than half a century ago and has delivered more disappointments than results,” he says.

So we’re back to the more basic question: why only three dimensions? Perhaps because some aspect of our universe wouldn’t work otherwise. The precise degree of quantum weirdness we observe (see page 49) seems only possible in 3D space, for instance. And Susskind points out that in any other

“Atoms, planets and stars may not form properly with fewer than three dimensions”

number of dimensions the electromagnetic and gravitational forces would have very different strengths. With fewer than three spatial dimensions, for example, gravity does not lead to attractive forces. Atoms, planets and stars would not form properly – and humans would not be around to ponder the existence of dimensions.

Did such a peculiarly curiosity-friendly 3D universe arise as part of a multiverse” in which every possible type of universe exists, a possibility espoused by string theory? Or is it just one of a kind? That’s a toughie, but either way, we’re still a distance away from explaining the essential three-ness of space, says Randall. “I think it would be lovely to have an answer, but as of now we don’t.”

Richard Webb

"It would take a billion years for just a few of the atoms in a pane of glass to shift at all"

WHAT IS GLASS?

FORGET the hoary myths peddled by tour guides at old European churches and cathedrals. Medieval window panes are sometimes thicker at the bottom not because of the slow flow of glass over centuries, but because of the uneven way molten glass was originally rolled into sheets in the Middle Ages.

Glass is not a slow-moving liquid. It is a solid, albeit an odd one. It is called an amorphous solid because it lacks the ordered molecular structure of true solids, and yet its irregular structure is too rigid for it to qualify as a liquid. In fact, it would take a billion years for just a few of the atoms in a pane of glass to shift at all.

But not everything about glass is quite so clear. How it achieves the switch from liquid to amorphous solid, for one thing, has remained stubbornly opaque.

When most materials go through this transition between liquid and solid states, their molecules instantly rearrange. In a liquid the molecules are moving around freely, then snap! – they are more or less locked into a tightly knit pattern.

But the transition from the glass-blower's red-hot liquid to the transparent solids we drink from and peer through doesn't work like that. Instead of a sudden change, the movement of molecules gradually slows as the temperature drops, retaining all the structural disorder of a liquid but acquiring the distinctive physical properties of a solid. In other words, in all forms of glass we see something unusual: the chaotic molecular arrangement of a liquid locked in place.

The process underlying this strange behaviour remains an open question. "The number of explanations almost matches the number of researchers," says Hajime Tanaka at the University of Tokyo in Japan.

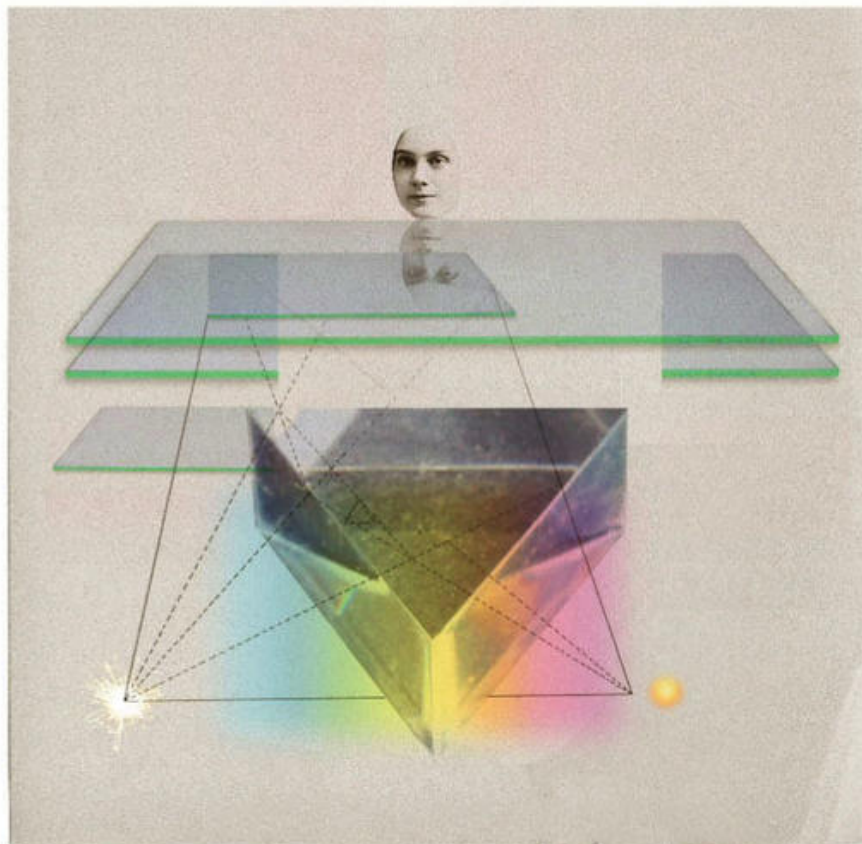
One possibility is that it's all down to energy use. According to the laws of thermodynamics, which govern how energy is transferred within a system, every collection of molecules is driven to find an arrangement with the lowest possible energy. But within any given system some patches do better than others, meaning different groups of molecules settle into different configurations – and, overall, into an irreconcilably chaotic arrangement.

But even if we put it down to thermodynamic laws, it's not clear what exactly drives glass's strange behaviour. The push for low energy

might be the prime mover. Then again, it could be the irrepressible tendency towards a maximum state of disorder. That's a perfectly plausible proposal, though it raises the troubling question of how ordered solids manage to survive.

Tanaka is not giving up just yet. "So far crystallisation and glass transition have been studied independently," he says. But Tanaka believes that glass may form in a manner not all that different from crystals, which have proved an easy target for analysis thanks to their repeating geometric structures. If he's right, maybe glass will finally become crystal clear.

Gilead Amit



MATTHEW RICHARDSON

HOW LONG DOES A PROTON LIVE?

THE BIBLE of fundamental physics, *The Review of Particle Physics*, devotes several pages to the ways a proton might fall apart. Each “decay mode” comes with an estimate of how long you might expect to wait to see one of these particles, bedrocks of the atomic nucleus, disintegrate that way. The unit of time is 10^{30} years – thousands of billions of billions of billions of years. Our stripling universe is a mere 13.8 billion years old, so this is a judicious, scientific way of saying that no one has ever seen a proton decay.

It’s not for want of looking. Super-Kamiokande, a 50,000-tonne tub of ultra-pure water under a mountain in central Japan, is one place where researchers are watching out for the pop and fizzle of a dying proton. The experiment’s results to date suggest the proton’s lifetime is probably more than 10^{34} years.

You’d think people would be pleased that the particles we’re all made of are stable. Physicists too: their “standard model” of particle interactions firmly indicates that protons, as the lightest particles constructed of three quarks, should never decay.

So why is “never” not good enough? The answer is that few believe the functional but ramshackle standard model is up to snuff. So-called grand

“Should we be worried if one of the fundamental components of you and me is a little wobbly?”

unified theories provide a more coherent account of three of nature’s forces – gravity remains aloof – at the price of the proton decaying. “It’s the signal of a grand unified theory,” says Benjamin Allanach, a theorist at the University of Cambridge.

Not only that, but these ambitious

models predict the proton should live for somewhere between 10^{30} and 10^{35} years – just the range experiments are now probing.

“We’re entering the really interesting area where you can start to rule these theories out,” says Allanach. “Or if they are correct, you should start seeing protons decay.” It could be a long wait: pushing the minimum lifetime up by a factor of 10 means watching for 10 times as long.

So should we be worried if one of the fundamental components of matter,

the stuff that makes up you and me, proves to be a little wobbly? Not really: our bodies do not make good observatories for proton decay. “From my back-of-the-envelope calculation, it would be a rare person that would experience a proton decay in their lifetime,” says Allanach. And the universe has so many protons that we’ll be long gone before they run out.

In the meantime, here’s the best answer we have for the lifetime of a proton: a very, very long time.

Richard Webb

IS THE UNIVERSE INFINITE OR JUST VERY BIG?

WE’VE known the size of Earth since the time of the ancient Greeks. The sun, solar system and Milky Way? No problem. But when it comes to the size of the universe, we haven’t got a clue.

“It’s weird: the size of the observable universe is one of the more precisely known quantities in astronomy, but the size of the whole universe is one of the least well-known,” says Scott Dodelson, a cosmologist at Fermilab in Batavia, Illinois.

One way to think about the size of the observable universe is to consider how far light emitted at the big bang could have travelled by now. According to our best cosmological models, that distance is about 46 billion light years. This is the cosmic “horizon”, a sort of three-dimensional equivalent of the 2D-horizon we see on Earth.

“That is as far as we can see and how big, empirically, we can observe the universe to be,” says Adam Riess of Johns Hopkins University in Baltimore, Maryland, who shared the Nobel prize in 2011 for the discovery that the universe’s expansion is accelerating. “Of course we are pretty sure it goes out much farther.”

Why? Because the universe looks very similar no matter which way you look. Take the cosmic microwave

background (CMB), the radiation left behind by the big bang. It is largely uniform across the sky, and we have no reason to think that would change beyond the cosmic horizon. There are no signs the universe is tailing off, so it would be a surprise if it abruptly ended.

Daniel Eisenstein of the Harvard-Smithsonian Center for Astrophysics says that if the universe is only a little bit larger than what we see, we might expect to find hints of structures much larger than galaxy filaments – formations of superclusters of galaxies. These hints would show up as wild variations in the temperature map of the CMB.

But they don’t, which implies that the universe is much larger than our little observable corner. If that’s the case, Eisenstein says it will be a struggle to figure out how big it is. “It might be a million times larger, or a trillion, or even infinite.”

A truly infinite universe might be tough for us to comprehend. Particularly perplexing is the idea that if the universe is infinite now then it must always have been so, even during the earliest moments in its history when the distances between objects were much smaller. But we would have to go a long way to rule it out.

MacGregor Campbell

That's odd...

From aberrant particle decays to strange patterns in the big bang's afterglow, there's no shortage of hints that our current theories don't provide a full picture of reality. **Michael Brooks** checks out the biggest anomalies in physics

1. UNRULY PENGUINS

On the trail of how it all began

Why does matter exist? We wouldn't be around to ask the question if it didn't, but our best theory of material reality implies that the existence of stable matter is an anomaly. So how did everything around us come to be?

We don't have an answer. But in our efforts to make sense of this, the anomaly to begin all anomalies, we are uncovering other hints that our understanding of the stuff contained in the universe is far from complete.

That understanding is rooted in the standard model of particle physics, the quantum-theory-based melange that bundles up our knowledge of all the forces of nature besides gravity (see diagram, page 56). One of its revelations is that every fundamental matter particle has an antimatter twin – a particle identical in every way apart from having the opposite electric charge. For the familiar negatively charged electron there is a positively charged “positron”, and so on.

The big bang should have made equal amounts of matter and antimatter. But here's the thing: when matter and antimatter meet, they annihilate in a puff of energy. So neither should have survived the early days of the universe.

Yet one of them did. Various experiments have tried to find some mismatch between processes involving matter and antimatter to

explain this. The latest is LHCb at the CERN particle physics lab, which is looking for an imbalance in decays of particles known as mesons, made up of a quark and an antiquark.

In 2011, one result looked promising: a type of D meson decayed at a different rate from its mirror version with quark and antiquark reversed. This anomaly disappeared when more data came in. Meanwhile, others arose.

For instance, heavier B mesons were found to be decaying into tau particles more often than the standard model predicts. Tau particles, along with muons, are just heavier versions of the electron. According to the standard model, once you adjust for their different masses, B mesons should decay into all three at the same rate.

THAT'S ODD: UNRELIABLE URANUS

Small anomalies between the actual orbit of Uranus and that predicted by Newtonian gravity led French mathematician Urbain Le Verrier to predict the existence of an eighth planet in 1846. Following Le Verrier's lead, Johann Galle of the Berlin Observatory discovered Neptune barely a month later.

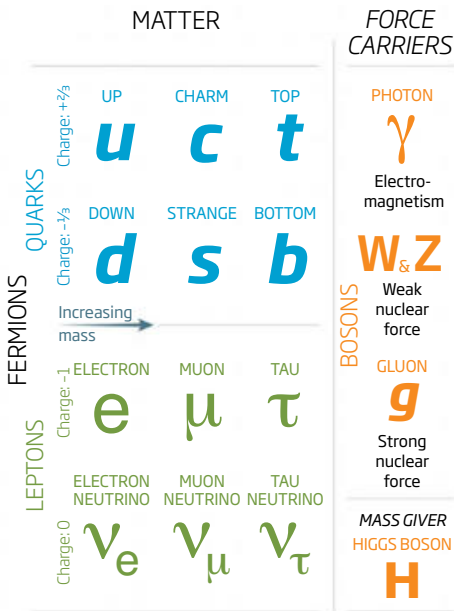
Such decays are known as “penguin” processes, supposedly because the standard diagrams physicists use to sketch them out end up looking rather like penguins. Unbalanced penguins have now popped up in three different experiments, including LHCb. The energies and trajectories of muons ➤





The standard model

The panoply of particles within the standard model of particle physics explains the workings of all visible matter and three of the four fundamental forces, gravity excluded



- Every **quark** and **lepton** has an antiparticle twin with the opposite electric charge
- **Quarks** clump together as composite particles made either of a quark and antiquark (**mesons**) or of three quarks or three antiquarks (**baryons** such as protons and neutrons)

produced in B meson decays are also persistently aberrant in LHCb data. “This anomaly stands,” says Guy Wilkinson of the University of Oxford, who works on LHCb.

Statistically speaking, none of the anomalies is significant enough to definitively say that something fishy is going on. But they do point to at least a shared misunderstanding, or false assumption, about the standard model. “This could be an indication of new physics,” says Valerie Gibson of the University of Cambridge and LHCb.

Perhaps B mesons decay momentarily into as-yet-undetected particles before decaying further into muons, skewing their final distributions. One favoured culprit is a leptoquark – a kind of hybrid of lepton- and quark-type particles. Another is a new kind of Higgs boson. But these are still little more than speculations. “We will have to wait for a couple of years to know more,” says Wilkinson.

Solving the original riddle of the matter-antimatter anomaly might take considerably longer, judging by the lack of any hint of an imbalance big enough to explain it. But it is the original proof that small anomalies can have big consequences.

started in the same place, in the pinprick of the big bang. But there are more than a few hints it ain’t necessarily so.

They are most obviously seen in the cosmic microwave background (CMB), radiation sent scudding across space-time some 380,000 years after the big bang, as it pinged off the first atoms that formed in the cooling universe. The atoms would have been uniformly distributed, more or less, giving the CMB a uniform temperature – now a frigid 2.725 kelvin, after more than 13 billion years of cooling. Small patches are a little hotter and cooler, but only by a few hundred-thousandths of a kelvin. These indicate small matter inhomogeneities that you would expect because of random quantum fluctuations in the density of the early universe. These blobs would later become the seeds for structures such as stars and galaxies.

So far, so good. But in 2005, Kate Land and João Magueijo at Imperial College London discovered a string of hot and cold spots stretching on an axis across the cosmic microwave background – something entirely incompatible with a uniform universe.

The most accurate maps of the CMB to date, courtesy of NASA’s Planck satellite, confirm the existence of this “axis of evil”, as well as a cold spot much larger and much colder than should occur in a uniform bath of radiation. Add that to a handful of other, more technical but also persistent anomalies, and cosmologists are left scratching their heads. “For a long time, part of the community was hoping that this would go away,” says Dominik Schwarz of the University of Bielefeld in Germany.

But it hasn’t. Exotic explanations for the patterns are that they result from collisions with another universe, entanglement with another cosmos or a “phase change” in the early universe – something akin to ice melting into water. At the other end of the scale, the anomalies could still be a statistical fluke born out of random variation, says Jo Dunkley,

2. THE AXIS OF EVIL

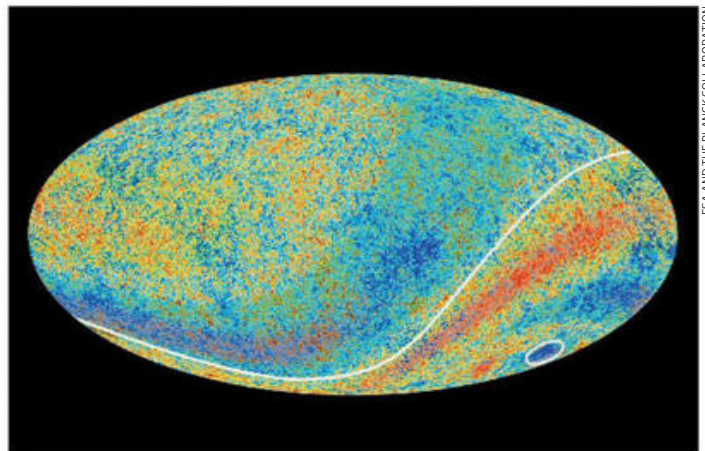
Anomalies in the cosmic microwave background cut through the universe

It’s not just particle physics that has its standard model; cosmology does, too. While our picture of the very small is rooted in quantum theory, our model of the universe at large is based on general relativity, Einstein’s theory of gravity.

General relativity’s equations are notoriously complex. Making a workable cosmological model out of them requires a crucial simplifying assumption: that the universe is pretty much the same on all scales and in all directions. That seems reasonable enough, given that everything in the universe

THAT’S ODD: MERCURY’S WOBBLE

Following up on the problem with Uranus (see page 54), in 1859 Urbain Le Verrier showed that Newtonian gravity cannot accurately predict the position of Mercury’s closest approach to the sun, its perihelion. A planet named Vulcan proposed to exist between Mercury and the sun failed to turn up. The anomaly persisted – until Newtonian gravity was itself blown away by Einstein’s general relativity in 1915.



The cosmic microwave background radiation is not the same temperature all over

a cosmologist at the University of Oxford – after all, we only have one sky to look at. Efforts are now afoot to measure the polarisation of the CMB. If the polarisation map also contains anomalies, that will strengthen the case for re-examining our cosmic model.

That could mean a long, hard look at the homogeneity assumption. Maybe there is a skew introduced because the universe is different outside our particular patch – if Earth were sitting in a giant void of lower than average density, for example. Or perhaps something in those quantum fluctuations caused the early universe to generate less structure over the largest scales, altering the CMB's properties. "These anomalies could certainly teach us about things that might be going on beyond the scale of our cosmic horizon," says Dunkley. "Right now there isn't a good model that fits them, but that doesn't mean there isn't one out there."

Future surveys of the large-scale structure of galaxies could give us a wider perspective. Meanwhile there is also everyone's least favourite option: that the universe is, for some unknown reason, just not homogenous or isotropic on any scale. If so, there'd be no exciting new stuff to investigate, just a long hard slog to fully understand what we already know.

3. MISSING NEUTRINOS

There could be an even more elusive particle

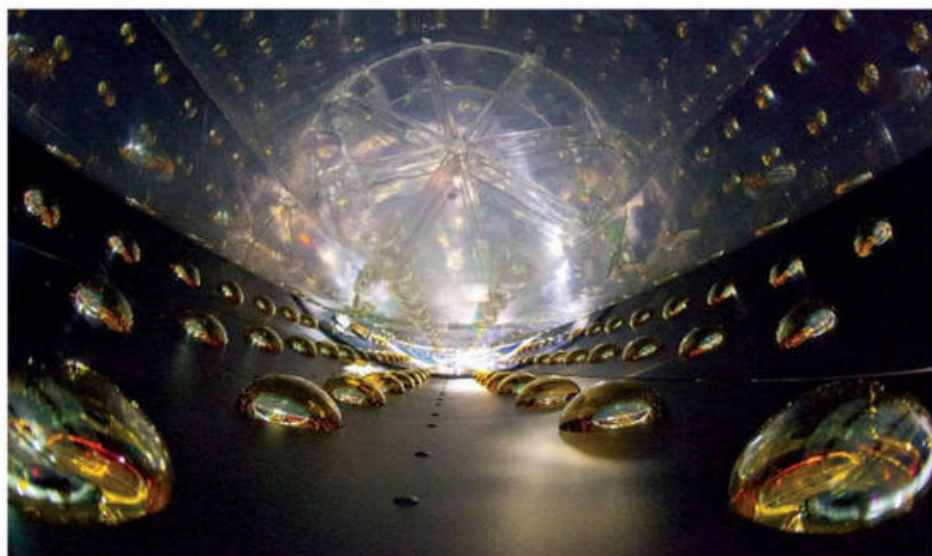
Study the standard model of particle physics at any length, and you might find yourself musing about the quasi-mystical significance of the number three (see diagram, top left).

Among the matter particles, there are three quarks – up, charm and top – with the same electric charge, differing only in mass. Then another group of three quarks – down, strange and bottom – for which the same pattern holds. Then three charged leptons, the electron, the muon and the tau: again, same charge, different mass. And finally, three distinct "flavours" of chargeless, near-massless neutrinos

Except maybe not that last one.

Neutrinos are particles that interact only via the weak nuclear force that governs radioactive decay. Trillions of the lightest type, electron neutrinos, are generated in reactions in the sun and pass through you every second. They will also pass through Earth without a blip.

Fiddly measurements over decades have revealed that a sizeable portion of this flux is going missing. This "solar neutrino problem" was resolved conclusively only in 2001, when electron neutrinos were shown to be shape-shifting, or "oscillating",



ROY KALTSCHMIDT, LAWRENCE BERKELEY NATIONAL LABORATORY

Daya Bay's neutrino detectors suggest a puzzling shortfall in these elusive particles

into muon and tau neutrinos on their way to us. That breakthrough was awarded last year's Nobel prize in physics.

At that point we might all have lived happily ever after, had not a series of detectors, starting with the Liquid Scintillator Neutrino Detector at Los Alamos Laboratory in New Mexico in the 1990s, begun to see more experimental blips. The blips suggested that there were not merely three types of neutrino, but four – or more. In 2011, an analysis of neutrinos emitted in nuclear reactors found there were too few antineutrinos compared with neutrinos – a shortfall confirmed in February this year by researchers from the Daya Bay reactor neutrino experiment in eastern China.

One explanation is that neutrinos briefly oscillate into unobserved "sterile" neutrino states that don't even interact through the weak force. That is uncomfortable not just because it breaks the rule of three. If sterile neutrinos exist, our best guess is they should be very heavy. These, however, seem to be very light and recent research almost certainly rules out the sterile neutrino theory (see "Neutrinos", page 42). Nonetheless, some detectors are looking for sterile neutrinos and, in February, CERN gave the go-ahead for the SHiP – Search for Hidden Particles – experiment to seek out heavier versions.

Neutrino physicist David Wark of the University of Oxford does not deny the neutrino anomaly exists. "The most recent measurements from Daya Bay confirm it," he says. But he is sceptical the new searches will find anything, because these results also reveal that our predictions for the overall numbers of neutrinos reactors should be pumping out don't tally with what we see. This implies our models may be at fault, says Wark – rather than our basic understanding of physics.

4. QUANTUM ENTANGLEMENT

Space and time cannot be what they seem

Imagine you could exert an instant influence on a particle hundreds of kilometres away. Actually, little imagination is needed. Such entanglement – or "spooky action at a distance", in Einstein's derisive phrase – is a consistent effect in the quantum world.

So that's not the anomaly. The anomaly comes in what this tells us about our perception of space and time.

This was brought into sharp relief through a series of experiments based on

THAT'S ODD: THE PIONEER ANOMALY

The unexpected slowing of the two Pioneer spacecraft as they crossed the solar system excited interest from the late 1990s as it indicated a possible deviation from general relativity's predictions. Heat recoil from the spacecraft's thermoelectric generators now seems to be the most likely explanation.

theoretical work done by the Irish physicist John Bell in the early 1960s. He worked out a mathematical way to tell if a measurement on one quantum particle (a photon of light, say) truly could change the result of a measurement carried out on another particle immediately afterwards, or whether some invisible, non-quantum influence was responsible.

Implementing Bell's test experimentally proved fiddly. The first attempt was made by a team of French physicists in 1981, with the result suggesting that only quantum effects could explain what was observed. But it was only last year that physicists at the University of Delft in the Netherlands devised a version of the test that conclusively ruled out standard information transfer, ➤

random particle fluctuations or detector snafus as the source of the effects. “This allows us to certify that the problem is not a feature of a particular setup or a consequence of the way in which an experiment was performed, but really points towards a fundamental feature of nature,” says Jean-Daniel Bancal of the Quantum Optics Theory Group at the University of Basel in Switzerland.

And the result is clear. In the quantum world, our normal understanding of space-time, and cause and effect within it, dictated by our intuitive sense of how the world works, does not apply. There is something we are just not getting.

What’s also clear is that since photons, electrons and other quantum particles can become entangled and follow these obscure rules, we can begin to devise experiments using them to explore the

THAT’S ODD: THE ACCELERATING UNIVERSE
By any standards, this is an anomaly too large to ignore: distant supernova explosions are consistently dimmer than they should be, indicating they are further away than we expect. The standard explanation – that space’s expansion is speeding up thanks to an invisible “dark energy” that makes up two-thirds of the universe’s energy – replaces a big anomaly with an even bigger mystery.

true nature of space-time. “These are particles we can manipulate,” Bancal says. “So we can consider using them to access [this layer of reality] indirectly.” How exactly to do that is a problem we’re still wrestling with, though – and until we find an answer, this is one anomaly our brains are hard-pressed to explain.

5. FAST RADIO BURSTS

Made by aliens – or burping black holes?

Occasionally, radio telescopes detect a burst of energy that lasts just a few milliseconds but is equivalent in energy to the sun’s output over the course of a month. And then, almost as suddenly, there’s nothing.

This has been happening for 15 years now, and the source of these “fast radio bursts” remains unexplained. The events all have subtly different characteristics. The best data set comes from the Arecibo receiver in Puerto Rico, which has observed bursts that repeat, sometimes after just a few hours. So the bursts can’t just be from a single catastrophic event, such as a stellar explosion.

There’s also confusion as to how far away the sources are – some say billions of light years away, others say much closer. Tinfoil-hatted options such as alien spacecraft or one of our own military satellites are now more or less ruled out thanks to the Arecibo observations, says John Learned of the University of Hawaii. “The Arecibo multiple detections over a period of many days all came from the same location in the sky, so forget a human or alien satellite,” he says.

There have been speculations that the bursts arise as quantum gravity effects cause a black hole to explode. Another possibility is that they are caused by pulsars bumping into asteroids. Yet another is that they come from an as yet unknown class of objects, says James Cordes of Cornell University in Ithaca, New York. His own favoured explanation is at least in the realm of the known: a neutron star, perhaps orbiting a black hole and certainly in a galaxy outside our own. If so, what a neutron star is doing to emit the bursts is a mystery.

6. THE HIERARCHY PROBLEM

Gravity is strangely supine

Here’s an anomaly as old as your fridge magnet: how come gravity is so weak?

Hang on, you might say: gravity is strong enough to keep my feet on the ground, and no space agency firing craft into orbit would ever describe gravity as weak. But the mystery for physicists is why that force is so puny compared with the electromagnetic force that it doesn’t rip that magnet off your refrigerator – we’re talking about the pull of an entire planet, after all.

This mismatch between gravity’s strength and that of the other forces of nature goes by the name of the hierarchy problem. Because, uniquely, gravity is not yet described by a quantum theory, it’s not easy to quantify the problem’s size, but one measure is the Planck mass, a quantity that gets bigger the weaker gravity is. In our cosmos the Planck mass is huge. It is some 10 quadrillion times bigger than the mass of the W and Z bosons that define the strength of the weak nuclear force, for example. In fact, it is huge compared with all masses that pop up in the standard model. “The question is not why the Planck mass is big; the question is why it is big compared to the masses of all the known particles,” says theoretical physicist Matt Strassler. “The puzzle is something you can phrase either as the Planck mass being large or particle masses being small.”

Explanations following one route often invoke the idea of “fine-tuning”: that we just happen to live in an unnatural part of the universe where gravity is just right, so atoms, stars, planets and people have come to exist. Or they propose large extra

The Arecibo receiver has seen repeated bursts of searing radio energy



ROGER RESS/EVERETT/CORBIS



ILLUSTRATION

Neutrinos captured at the South Pole carry more energy than we can explain

dimensions of space into which gravity “leaks”, so it appears diluted to us.

Alternatively, we can focus on the Higgs field, which generates particle masses. The low mass of the Higgs boson, discovered in 2012, indicates this field is not particularly strong, keeping all particle masses on the low side. Theories such as supersymmetry and technicolor focus on as-yet-undiscovered particles or forces whose effect is to restrain the Higgs field to the observed strength of almost – but not quite – zero.

Experiments aren’t helping decide between these options as yet. Supersymmetry – or indeed anything new besides the Higgs boson – has so far failed to make its presence felt in the particle smashes going on at the

THAT’S ODD: SPEEDING GALAXIES

It’s another big ‘un – studies of galaxies and galaxy clusters consistently indicate that they are rotating too fast for the amount of matter that meets the eye. Try as we might, we haven’t yet been able to pin down the culprit – non-interacting “dark matter”, which seemingly outweighs normal matter by five to one.

Large Hadron Collider. “Not finding anything else yet leaves us at sea,” says Strassler.

The hope is that future runs of the LHC, which is now operating at maximum energy and generating more particle collisions than ever, could give us more of a clue.

That’s why the recent appearance of blips in the LHC data, indicating the existence of a particle six times as massive as the Higgs

boson and not predicted by the standard model, made many a physicist’s heart beat a little swifter until it was dismissed as an anomaly. But we can never rule out other blips appearing – or what, if any, solution to the problem of gravity they might support.

7. ULTRA-HIGH-ENERGY NEUTRINOS

Why so energetic – and why not more?

Bert, Ernie and Big Bird came from outer space. We are not talking about the *Sesame Street* characters, but three neutrinos with anomalously high energies spotted by the IceCube neutrino detector at the South Pole in 2013 and 2014. They have since been joined by dozens more, all with energies in the petaelectronvolt (PeV) region – that is, a million billion electronvolts.

One problem is that we have no clue what process could have given these neutrinos that much energy. Another is that, if these exist, we can’t think of a reason why even more energetic ones shouldn’t, too.

We know that neutrinos are created by extremely high energy processes. Many were born in the moments after the big bang. Others come from supermassive black holes at the centres of galaxies, or hypernova star explosions. Suspicions that the flux of neutrinos from outer space drops off before it reaches petaelectronvolt energies only come from never having seen anything more

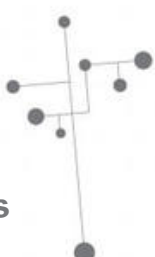
energetic than Bert, Ernie and co. Nobel prizewinner Sheldon Glashow has used the standard model of particle physics to predict a flux of neutrinos with even higher energies of 6.4 PeV. These should be produced when an antineutrino and an electron collide, creating a W boson and sloughing off a neutrino.

So why haven’t we yet seen anything like this? “Confusing?” says Thomas Weiler of Vanderbilt University in Nashville, Tennessee. “Damn right.”

Given we have multiple detectors capable of spotting such high-energy particles, either we need to rethink the idea that they can exist in the first place, or propose some mechanism that would slow them to lower energies.

Together with University of Hawaii physicist John Learned, Weiler has taken the second tack. Every quantum particle has an associated wavelength. The higher the energy of the particle, the shorter that wavelength is. One possibility is that the wavelengths of the high-energy neutrinos are so short that they may be encountering a kind of friction from a pixelated, quantised structure of space-time.

“If we are right, the super-short wavelengths of the neutrinos are sampling the structure of space, and there will not be higher energy neutrinos seen,” says Learned. That would also be our first experimental clue about what a theory that melds quantum descriptions and general relativity should look like. This is a huge leap. “Probably this is too crazy, and wrong,” says Learned. “But still there is a delightful anomaly here.” ■



Us versus The Universe

Who said the laws of physics are immutable? Anil Ananthaswamy and Jacob Aron set out to bend the rules

OK, SO no one said understanding the cosmos was easy. Try as we might to understand natural phenomena, we often run smack bang into limits set by the laws of physics. Does that put us off? Not a bit of it. Using our smarts, we can bend some laws or even use one law to sneak around another. Take that, universe! Read on to find out more...



SQUEEZED KNOWLEDGE

Heisenberg's quantum uncertainty principle

IN FEBRUARY 1927, a young assistant to the quantum pioneer Niels Bohr had a brainwave about why measuring electrons provided consistently fuzzy answers. "The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa," he wrote.

Werner Heisenberg had discovered his famous uncertainty principle - a cornerstone of quantum physics that limits how well we can know not just position and momentum, but a whole host of "complementary" pairs of quantities.

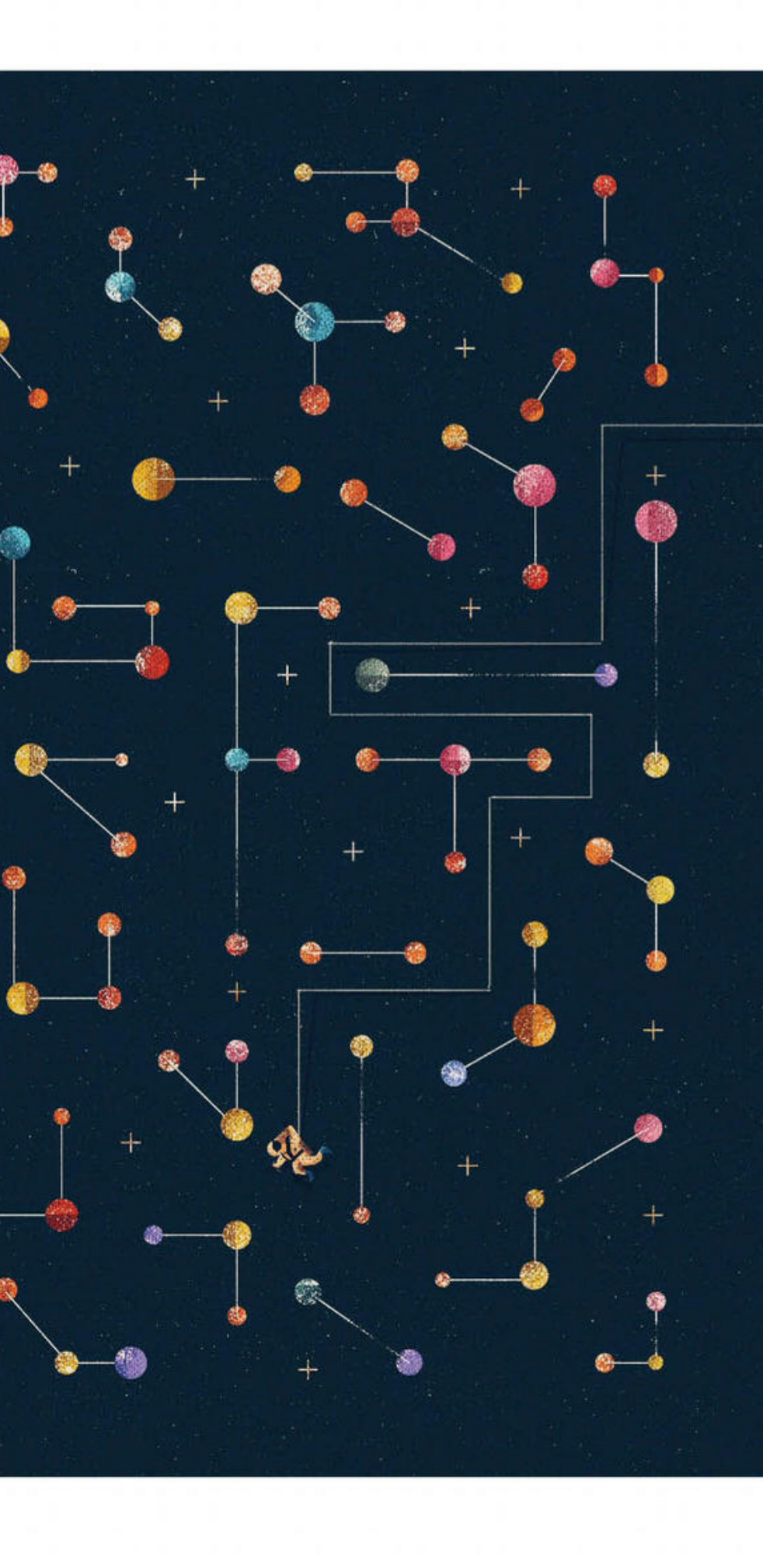
Uncertainty has practical consequences. Take

gravitational waves, a recently verified prediction of Einstein's general theory of relativity. Experiments to detect these ripples in space-time rely on measuring tiny disturbances to laser light bouncing between distant mirrors. "People believed there was a fundamental limit for the sensitivity of such detectors, the standard quantum limit," says Karsten Danzmann of the Max Planck Institute for Gravitational Physics in Hanover, Germany, who works on one such detector, GEO600.

In fact there is a loophole. Uncertainty says you can learn more about one quantity by knowing less about its complementary quantity. To detect high-frequency gravitational waves, you need to know accurately the number of photons hitting the mirrors, but are less concerned about its complementary quantity, their arrival times. Squeeze all the uncertainty into the photons' timing, and you can increase your detection-sensitivity dramatically.

"Squeezed light" was first proposed by physicist Carlton Caves in the 1980s, but it is only in the past decade that physicists have mastered the necessary techniques, which involve splitting one normal photon into two with squeezed uncertainty. GEO600 now uses the technique routinely - and there seems to be no limit in sight. "Squeezing will improve, slowly, but steadily," says Danzmann.

DANI MATUTINA



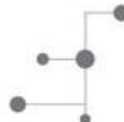
A SHINING EXAMPLE

Diffraction limit

TALK about microscopes and you bump up against the diffraction limit. Traditional microscopes cannot see objects smaller than about half the wavelength of light, because of how light bends and scatters at the edges of lenses. The limit equates to about 200 nanometres for visible light. "This has been impeding light microscopy throughout the 20th century," says Stefan Hell of the Max Planck Institute for Biophysical Chemistry in Göttingen, Germany.

Hell won the 2014 Nobel prize in chemistry for his part in overcoming this problem. He pioneered an ingenious technique called stimulated emission depletion microscopy, whose basis is shining a beam of light at stained biological tissue so that the illuminated part fluoresces. Because of diffraction, the smallest this spotlight can be is 200 nanometres. Hell's workaround is to add a second beam made so that its spot of light is dark at the centre. When the second beam is perfectly aligned with the first, it partially cancels the sample's fluorescence, leaving only the part corresponding to its dark patch fluorescing. This patch can be made much smaller than 200 nanometres, allowing what was previously thought impossible – the imaging of individual molecules. "The diffraction barrier has definitely been overcome," says Hell.

There is another way to dodge the diffraction limit. A class of engineered "metamaterials" have properties not found in nature and can bend light the opposite way. Superlenses made from metamaterials have smashed the diffraction limit.



LESS THAN NOTHING

Absolute zero

DEFINING a temperature scale is easy. Fire is hot; ice is cold; draw a line between the two and there you are.

But what makes fire hotter than ice? The 19th-century physicist William Thomson, later Lord Kelvin, gave one answer. He defined temperature in terms of kinetic energy. In hot bodies, particles are moving around a lot; in cold ones, not so much.

Kelvin's scale implied a natural lowest temperature at which particles stop moving completely. It is impossible even to make something reach this "absolute zero", since that would imply the existence of



something even colder to cool it with – let alone leap to negative temperatures beyond it.

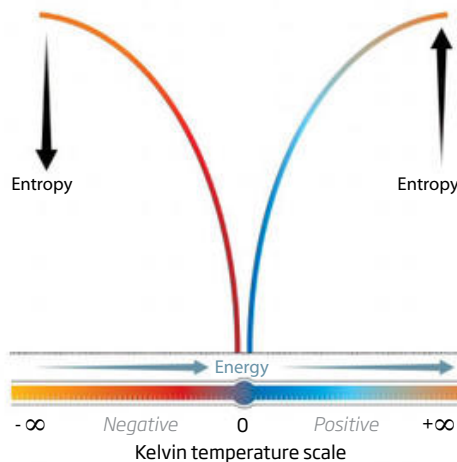
Or is it? It turned out later that temperature depends not just on particle energies, but how that energy is distributed: disorder, or entropy. Increasing entropy also implies heat flow – and temperature change. Because of the way Kelvin defined his scale, increasing a system's energy while reducing its entropy registers as a negative temperature. In fact, there is a whole mirror world of negative temperatures stretching towards absolute zero from negative infinity (see diagram, right).

Motion and disorder usually increase in lockstep, so states of increasing energy and decreasing entropy are not things we stumble across every day. But physicists can make them. A team led by Ulrich Schneider, then at the Ludwig Maximilian University of Munich, Germany, created a negative-temperature state by using lasers to manipulate atoms cooled to a fraction above absolute zero.

It's a bit of a cheat, really. Absolute zero still represents the lowest energy a system can have; it's just that Kelvin's scale doesn't necessarily reflect that. Those in the know prefer to speak of negative thermodynamic beta, which assigns the value of minus infinity to absolute zero and climbs smoothly upwards with increasing energy. Or maybe we should just stick to Celsius.

Wrong way round

Conventional, positive temperatures rely on energy and entropy both increasing. But when entropy decreases things can get even hotter – although these temperatures register as negative on the Kelvin scale



"A WHOLE MIRROR-WORLD OF NEGATIVE TEMPERATURES EXISTS BELOW ABSOLUTE ZERO ON THE KELVIN SCALE"

OUT OF THIS WORLD

Seismic limit

DETECTING ripples in space-time is, on paper, easy: you simply measure how passing gravitational waves disturb the transmission of laser beams bouncing between mirrors. The devil is in the detail, though. Because the disturbances are unbelievably tiny, physicists have had to invent all sorts of clever tricks in their efforts to detect them (see "Squeezed knowledge", page 60).

One limit looks impossible to dodge here on Earth, however: the seismic limit. Seismic motion from earthquakes around the world shakes the mirrors, causing noise that can overwhelm any signal. The mirrors can be shielded from most tremors, but ones below 1 hertz are trickier to cancel out. This quashes hopes of finding low-frequency gravitational waves emitted by pairs of dense stars, or stars captured by supermassive black holes. "That is probably a fundamental limit for the low-frequency sensitivity of any ground-based detector," says Karsten Danzmann of the Max Planck Institute for Gravitational Physics in Hanover, Germany.

The way around this limit is to fly your detector in space. The European Space Agency's eLISA mission, scheduled to fly in 2034, is three satellites flying in a triangle formation around the sun. Each satellite will fire laser beams at the others to measure precisely the distance and spot any telltale stretch-and-squash of space-time caused by a gravitational wave. Each side of the triangle will be a whopping 1 million kilometres long, which opens up the possibility of detecting gravitational waves we would never spot on Earth. "Any supermassive black hole coalescence, wherever and whenever it occurred in the universe, will be detectable with eLISA," says Danzmann.

TAKING OUT THE TWINKLES

Atmospheric limit

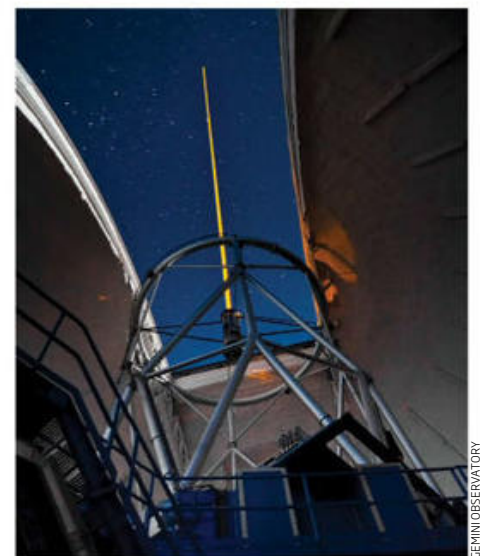
BUILD an 8-metre-wide telescope high up in the spectacularly clear Chilean Andes and it will see no better than a space telescope just 50 centimetres across. That's because of Earth's pesky atmosphere. Variations in temperature and pressure in the atmosphere's layers cause starlight to zigzag as it travels through. What to us is pretty twinkling makes for blurry images that limit observations.

We can't make the atmosphere any clearer, but there is a way around its limits. Shooting a laser into the night sky lights up a layer of sodium atoms 90 kilometres up, at the outer edge of the atmosphere. This creates an artificial guide star. Astronomers know exactly what it should look like without any atmospheric turbulence, so they can use the extent of blurring recorded by the telescope

to figure out how starlight has been affected. They use this information to rapidly move a small, deformable mirror in the telescope's eye view to cancel the atmospheric blurring.

One of the most sophisticated of these adaptive optics systems was recently installed in the 8-metre Gemini South telescope, atop Cerro Pachón in Chile. It uses five guide stars and three mirrors that change shape a thousand times a second. "In a given image, you get 10 to 20 times more information," says Benoit Neichel then at the Gemini South Observatory in La Serena, Chile.

Guiding light: shooting lasers into the sky allows astronomers to cancel out atmospheric effects



SIGNATURES OF THE INVISIBLE

Cosmic limit

IT'S the universe's first light. The cosmic microwave background (CMB) formed about 380,000 years after the big bang, when the fog of the early universe had cleared enough for light to travel unimpeded through the cosmos. We cannot see beyond this curtain of light to earlier times. It's the limit of our electromagnetic vision.

But not of all vision. Like footprints on an empty beach, imprints on the CMB tell the story of what happened before. Today we see the light, stretched in wavelength due to the expansion of the universe, as microwaves in the sky.

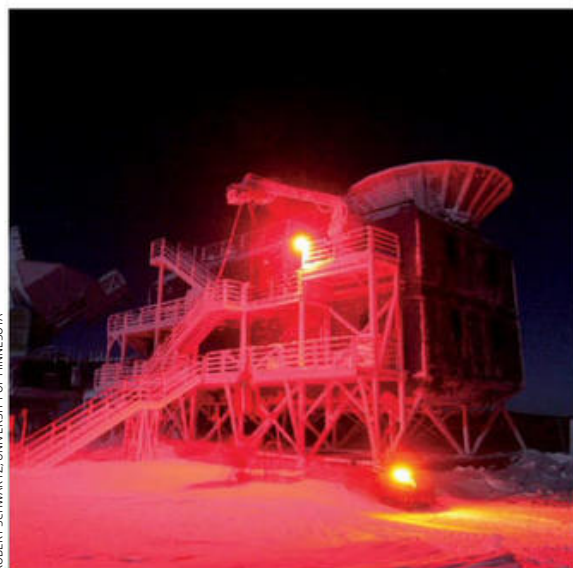
These microwaves have a temperature of 2.726 kelvin. In a technical tour de force, NASA's WMAP satellite was built to map variations in this temperature as small as 1 part in 100,000, across the entire sky. This revealed that the early universe contained relatively denser regions, which would become seeds for clusters and super-clusters of galaxies.

Events that happened even earlier,

when the universe was just 10^{-36} seconds old, are also thought to have left their mark. This is when the universe supposedly underwent a period of blistering expansion called inflation, sending ripples through space-time that polarised the light in a characteristic pattern.

In 2014 the BICEP2 telescope at the South Pole controversially claimed to have seen this faint signature, but the European Space Agency's Planck satellite ruled out the findings.

On Earth, the Large Hadron Collider at CERN, near Geneva, Switzerland, is also helping smash the cosmic limit - by showing us what the universe might have been like just microseconds after the big bang. The LHC does this by colliding lead ions accelerated to near light speed. The collision creates energies so high, at temperatures of about 5.5 million kelvin, that all matter disintegrates into its constituent quarks and gluons - a mini big bang whose quark-gluon soup is now being analysed.



ROBERT SCHWARTZ, UNIVERSITY OF MINNESOTA



IT'S NOT JUST A GOOD IDEA, IT'S THE LAW

Speed of light

If its results are confirmed, the BICEP2 telescope will have seen beyond the limit of cosmic sight

THIS T-shirt slogan has its basis in Einstein's equations of special relativity, but it obscures a subtle fact. "Conceptually, special relativity does not imply that nothing can travel faster than light," says Abhay Ashtekar, a theoretical physicist at Penn State University.

It says that if a particle is moving slower than the speed of light, c , only an infinite amount of energy will accelerate it above c . And if a particle is moving faster than c , you cannot slow it down to below c .

Some phenomena seem to violate this speed limit. Cosmic rays zipping through water create the optical equivalent of a sonic boom, which implies that they are going faster than light speed. But the rays are only exceeding the speed of light in water, not the speed of light in a vacuum, which is the ultimate barrier.

Galaxies that are at the edge of the universe are also moving away from us faster than the speed of light. However, this is due to the ongoing expansion of the universe, which is not really a velocity in the strict sense.

Something similar is true for quantum-entangled particles. When you measure one of a pair - no matter how far apart they are in the universe - you immediately influence the other.

This seems to be faster-than-light signalling, but if you try to use entangled particles to exchange information, you are again limited by the speed of light.

So while we've had a good ride breaking other physical laws, it seems nothing - not particles, not information - can break the universe's speed limit. ■

WHY THINGS MATTER

Pauli exclusion principle

DESPITE its name, this principle is pretty inclusive: it makes all normal matter what it is. Named after the Austrian physicist Wolfgang Pauli, who proposed it in 1925, it says that no two electrons in an atom can enter the same quantum state. This leads to atomic electrons filling an elaborate structure of higher and higher energies around the nucleus, explaining why atoms with different numbers of electrons have different properties. Without the Pauli exclusion principle, the chemical elements wouldn't exist.

The principle applies not just to electrons, but to all the particles that make up conventional matter, collectively known as fermions. Its influence extends even to the stars. Very dense cosmic bodies such as white dwarf and neutron stars resist collapsing inwards under their own immense gravity because the Pauli exclusion principle prevents electrons and neutrons from crowding together. In the case of white dwarfs, this holds until the body reaches a certain mass, when the force of gravity becomes overwhelming and the star explodes as a supernova. This

mass was first calculated by the Indian-American astrophysicist Subrahmanyan Chandrasekhar to be 1.4 solar masses, but has recently been observed to be even higher in some cases.

It all sounds pretty cast-iron. But as Deborah Jin of the University of Colorado and her colleagues found out in 2003, you can circumvent Pauli's principle - although only at low, low temperatures. When it's that cold, particles behave differently, and fermions can be encouraged to pair up. These paired particles dance to a very different tune, and the Pauli exclusion principle ceases to apply, enabling groups of them to all enter the same quantum state.

Jin's first creation of a "fermionic condensate" involved potassium-40 atoms, which act like very big fermions, cooled to within a whisker of absolute zero and nudged to pair up in a magnetic field. "In some ways you are getting around the Pauli exclusion principle," Jin says. Only in some ways: fermions on their own are still subject to its iron rule.

CHAPTER THREE
LIFE AND DEATH

The JOURNEY of a LIFETIME

Welcome, weary traveller. You've come a long, long way. You and the world around you are a temporary arrangement of matter and energy that took many billions of years to assemble. Imagine if you could deconstruct it all and trace each part's journey.

Many of the trillions of atoms in your body were forged in the incandescent cores of stars. What did they experience as they travelled through space? Some of the water in our cells has been through dinosaurs. And there are gems that have survived all of Earth's growing pains. Our travels continue: your physical body will eventually return to the stars. Even the act of looking at a distant constellation takes you on a strange journey through time and space.

Come with us on a selection of imaginary journeys that you will never take but, in some way, already have.

STARDUST TO STARDUST

TRAVELLER A calcium atom
ORIGIN The first stars
DESTINATION Your body,
and beyond
DURATION 13.5 billion years+

The calcium in your bones, like every other heavy atom in your body, was forged in the fiery furnace of enormous stars, 10, 100, even 1000 times the mass of the sun. This one, nestled inside your left collar bone, came from one of the universe's very first stars, born 550 million years after the big bang.

When its birth-star burst into a giant supernova, calcium fled the scene like an action hero diving out of an exploding car. It floated through interstellar space for millennia before joining a cloud of gas and dust dense enough to collapse into a new star, also destined to go supernova.

It is a cycle that repeated itself a few times until, some 5 billion years ago, the atom found its way into the cloud that became our solar system. The view from inside the iridescent haze would have been awe-inspiring. Nearby infant stars shone through like floating diamonds, their radiation sculpting the gas and dust into other-worldly sandcastles. Lost in their midst were

all the other atoms that would one day coalesce into your body.

Slowly, the haze contracted under its own gravity, compressing the centre until it was hot enough to ignite into the seed of a star. As the gases swirled around our newborn sun, they dragged the calcium atom into a giant spinning disc.

It took a further billion years for Earth to solidify from the cloud, with your calcium atom trapped inside it. And another 4.5 billion years passed before it ended up in the broccoli you had for dinner the other night. Along the way, it cycled through Earth's crust and oceans, a limestone cliff and a mollusc shell, until finally there it was in the field, sucked into the broccoli plant and onwards to your dinner plate.

You and your collar bone will only be here a short time, as far as the calcium atom is concerned. One day, it will flow out of the bone, into your blood and return to the earth in urine, where it can help other things grow.

In another 5 billion years or so, the calcium atom will look on as the sun collapses into a dense ball of carbon and oxygen, sloughs off the last of its gas and becomes a cool, puffy old star called a red giant. With time, its core will settle into a dense nugget called a white dwarf. The mass of the entire sun will be squashed into a volume about the size of our planet.

If Earth survives this process, it will quickly become a boring, lifeless rock - which shouldn't bother the calcium atom. Eventually, though, Earth may fall on to the surface of the

"Somewhere in the haze were all the atoms that would become your body"

white dwarf. If they bother to look, alien astronomers will see a smear of calcium in the dead star's spectrum. Our own astronomers have recently found similar signs of heavy elements in the spectra of white dwarfs in our galaxy.

But if the outer layers of the sun were to engulf Earth in its death throes and vaporise it... well, it is just possible that the calcium in your collar bone will be carried away as renewed cosmic dust - material for the next generation of stars. Lisa Grossman

ONCE, YOUR BLOOD WAS DINOSAUR URINE

TRAVELLER Water
ORIGIN A comet, smashed into Earth
DESTINATION This page
DURATION 4 billion years

Water's journey began 4 billion years ago when Earth's hellish, dry and volcanic surface was being pummelled by a relentless rain of comets and asteroids. Molecules of water trapped inside them spread across the surface of our planet, and 700 million violent years later, Earth's dry rock had been transformed into the familiar blue marble.

As temperatures rose, a water molecule was swept with billions more into a vast oceanic river that slowly made its way from one pole to the other. For millions of years, the molecule skirted continents, nudged the sea floor, helped to dissolve rocks and transport gases. It crossed the equator hundreds of thousands of times. It found itself at the surface of the sea, was warmed by the sun, rose high into the atmosphere and fell to ground in a raindrop. It seeped through cracks and became stuck in an underground aquifer for centuries. Eventually, as all water does, it found its way back to the ocean.

From 3.8 billion years ago, a new deviation became possible from its usual route of cycling around the oceans and atmosphere: it could be found inside living cells, keeping them alive.

And so, around 150 million years ago, our molecule finds itself in a lake on what will eventually become one of the great plains of North America. A brontosaurus cranes its neck down for a drink. The water roils around the beast's digestive system and is absorbed into its blood. Now it can perform the most important role Earth has found for it - enabling the basic chemistry of life.

In concert with other water molecules, it forces DNA, proteins and cell membranes into the correct shapes to function. It helps carry oxygen to the dinosaur's brain and shuffles electricity around a heart cell. For a week, it moves around the dinosaur's body, but the game is up once it reaches the animal's kidneys. The molecule is expelled in urine, taking with it some of

the brontosaurus's waste. It sinks through the ground and, like so many times before, finds its way through cracks and fissures and streams back to the oceans.

In subsequent millennia, our molecule finds its way into a whale's brain, an Antarctic ice sheet, a glass of water and a human heart. Later, it waters a pine tree. It sits for decades in the cellulose fibres of the tree's heartwood before the pine is felled and turned into pulp. The molecule stays in place as the pulp goes through chemical reactions, manipulations and dryings until it finds itself locked inside a sheet of paper. That paper is printed with ink. It is cut, folded and stapled. The water molecule sits, motionless, at the end of a sentence, this very one. **Alok Jha**

FROM A SANDWICH TO A SCREAM

TRAVELLER Energy
ORIGIN Your lunch
DESTINATION Your cells
DURATION Hours

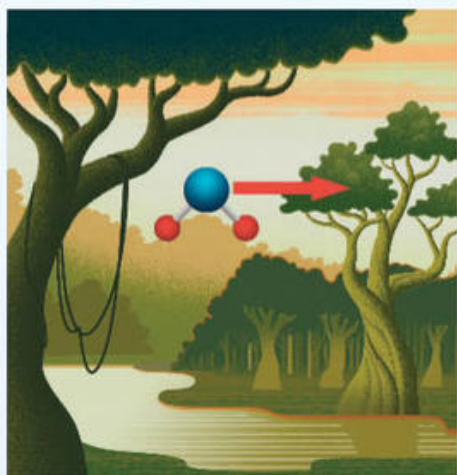
A typical sandwich contains billions upon billions of buzzing electrons. The bonds they form hold together the sugar, carbohydrate, fat and protein we call lunch. The energy in those bonds will eventually power your body, but it can do you no good locked in a sandwich. Luckily, electrons have you covered.

Our electron's journey begins with a bite. Attached to a starch molecule, it is pushed from your mouth to your stomach and then small intestine. Its starchy home is torn asunder by enzymes from the pancreas, and now our intrepid electron is adrift on a molecule of glucose.

A MOSASAURUS BREATHED INTO YOUR STOVE

TRAVELLER Carbon atom
ORIGIN A mosasaurus's breath
DESTINATION A coal-fired power plant
DURATION 65 million years

Sixty-six million years ago, a vast shallow sea covers swathes of North America – the Western Interior Seaway. A carbon dioxide molecule is expired into the tropical waters by an 18-metre-long aquatic mosasaurus. It embarks on a journey around the world, flitting between air and ocean, until...



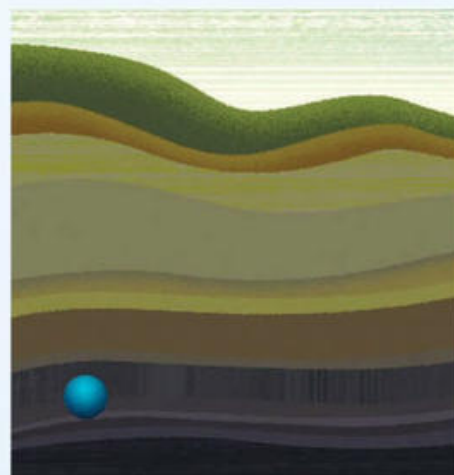
66 mya

Geological forces lift the bottom of the Western Interior Seaway and the sea is replaced by subtropical lakes and swamps. Having travelled around the world, our carbon dioxide returns to North America and is absorbed by a swamp tree. The tree dies, locking the carbon atom inside.



60 mya

Layers of decaying plants and river sludge pile up on the tree's remains. Rising temperatures and pressures crush them into a hard, dark rock: coal.



35 mya

Millennia pass slowly. Far above our carbon, the region begins to dry out. More and more sediment piles on top of the coal, burying it thousands of metres below the surface.

It crosses into the bloodstream, passing briefly through the liver, to join the rush of cells, chemicals and plasma that complete a circuit around the body roughly every minute. Before too long it finds its way into a muscle cell.

The interior of a cell is far from safe. The electron's glucose raft is quickly cut into pieces by a 10-step chemical disassembly line. Hanging on to one of the pieces, our electron is now headed for the cell's power plant: the mitochondrion. This is where the electron's energy truly comes into its own. Inside, it will enter the final stage of its journey: a series of reactions known as the

electron transport chain.

Like a boulder perched at the top of a hill, with a bit of a nudge, the electron tumbles from higher energy states to lower, releasing energy along the way. Enzymes manage the fall, stair-stepping the electron to ever-lower states.

Energy released at each step is used to drive a pump. Protons are pushed, one by one, across a membrane in the mitochondrion and pile up on the far side. Like fans desperate to get inside a stadium, the protons have a single drive - to get back through the membrane. As they push through molecular turnstiles, the energy they release

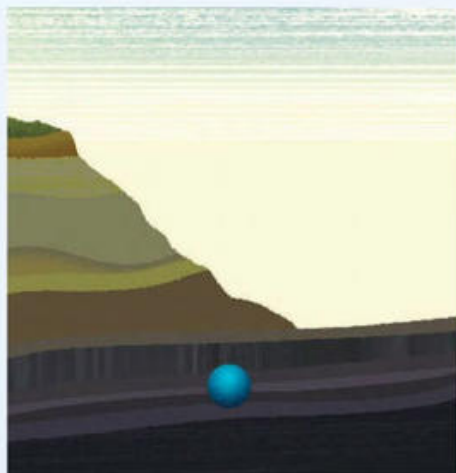
glues a phosphate to an ADP molecule: adenosine diphosphate is turned into adenosine triphosphate. You may have heard of it as ATP. This is the cell's ultimate source of energy.

By the time the electron has bumped its way down to the end of

"Like a boulder perched on top of a hill, with a nudge the electron tumbles, releasing energy as it goes"

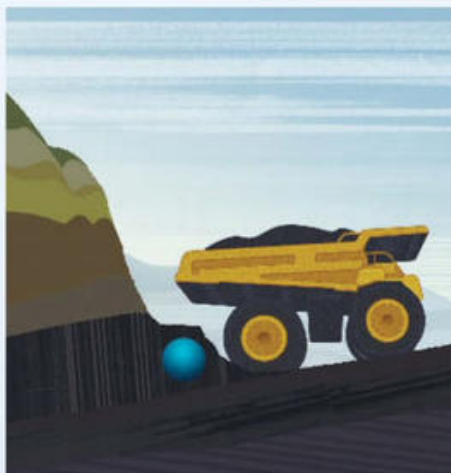
the chain, some 32 ATP molecules have been made. Drained, our electron joins forces with a leftover proton, and two of these hitch themselves to an oxygen to form water. Flushed out of the cell, the water molecule makes its way to the lungs and moistens your breath.

But the electron's energy lives on, in the form of ATP. When, a few hours after lunch, you stub your toe, it helps activate a muscle cell contracting the diaphragm. This expels carbon dioxide and our electron's water molecule out of your lungs. The molecule shoots past your voice box and out into the world as a cry of pain. MacGregor Campbell



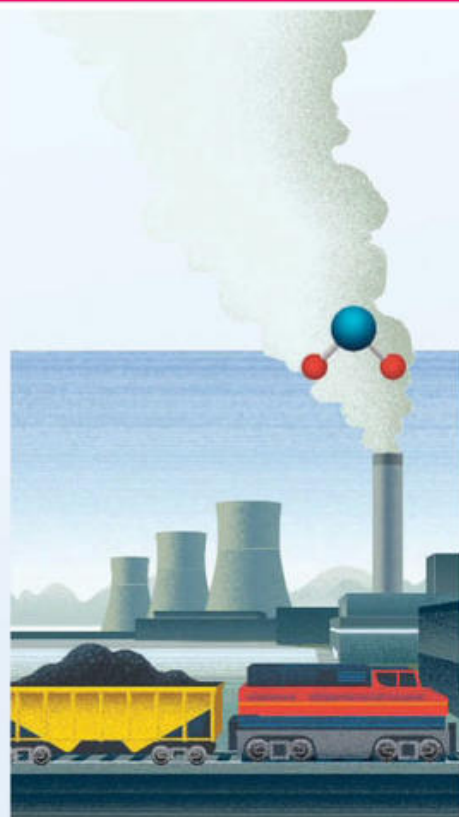
10 mya

Tectonic forces shift and the crust begins to rise. The pressure lessens. Rivers flowing from the majestic Rockies slowly erode the rock above. Our atom is part of what will come to be one of the largest coal seams in the world: the Powder river basin, stretching across Montana and Wyoming.



1970s

The ground trembles as huge machines tear out tonne after tonne of coal. Our carbon sees the light of day for the first time in 66 million years, and is headed for an entirely different, less peaceful destination.



In a furnace, millions of years of slow formation are reversed in an instant. The energy released by burning the coal briefly powers someone's stove. The fire binds the carbon to oxygen atoms. As carbon dioxide again, it escapes through the flue and into the atmosphere with countless others like it. Many more millions of years will pass before it returns to its deep-earth hideaway. **Catherine Brahic**

TO THE DEPTHS OF THE EARTH AND BACK AGAIN

TRAVELLER A gem as old as the hills
ORIGIN Earth's innards
DESTINATION Asia
DURATION 4 billion years

The zircon crystal comes into being deep inside a young Earth that is covered in ocean and pockmarked by volcanoes spewing white-hot lava. Hundreds of kilometres down, zirconium ions drift in magma droplets through the slowly creeping molten rock. A quirk of mantle currents gathers them beneath a new continent. The magma cools as it rises.

Crystals begin to grow, countless atoms slotting into place in perfectly regular mineral lattices. The zirconium ions form their own crystal, and theirs is quite special: a clear, millimetre-sized structure so hard that it will last for all of eternity – at least as far as Earth is concerned. It is a haven, too, for uranium atoms. As soon as they are encased in the crystal, they begin to decay into lead, starting an atomic clock that will tick for billions of years. Together the gem and its clock will travel the world.

There is no time for rest. The magma is stirring, rising towards a volcanic vent. The zircon flies out of the crust in a luminous whirlwind of hot gas and rock and is dumped in a thick layer of volcanic ash. Later, more ash layers pile above it, and eventually the volcano goes extinct.

Over millions of years, wind and rain slowly exhume the crystal and leave it exposed on a lifeless grey wasteland of rock

and rubble, under an atmosphere of carbon dioxide and methane. It is a dangerous place. Meteorites pound the planet and the thump of one landing nearby rearranges part of the zircon lattice.

A few thousand years pass. Storms slowly inch the crystal across the landscape until finally it tumbles into a river and is dragged out to sea. It's moving much faster now, pushed by currents across the sea floor. The long journey smooths its edges. Sand starts to pile on top of it, and for the second time it ends up deep inside Earth's crust.

When it returns to the surface over a billion years later, pushed up by tectonic forces, the lands and oceans have transformed. Some of the cells that float in the oceans have evolved to harness energy from the sun and are pumping oxygen into the air, which rusts any unstable minerals on the continents. The bare landscape around the zircon is now a pattern of browns and reds.

The crystal is washed into the sea once more, briefly trapped in a slimy mat of microbes, then buried for a third time. For 2 billion years, the tectonic plate it is trapped inside drifts across the globe, crosses the equator, then is crumpled as continents collide. The zircon is sheared and cracked.

It holds together – just. Part of its atomic clock is reset by migrations of uranium and lead; more scars that will one day tell the tale of its extraordinary voyage. As mountains rise above, the rocks around it begin to melt. New zirconium ions in the magma cover the ancient gem in a fresh crystal coat, with its own atomic clock.

Erupted to the surface for a third time, the battle-scarred and healed zircon lies on a humid, tropical landscape. The skies are alive with birds and in a nearby forest a new animal cry has joined the chorus: the first primate! In a flash of monsoon rains, the crystal is washed into a new river, a new sea and is buried again.

The next time it sees the light of day, 65 million years later, circumstances are very

“The tiny crystal is so hard that it will last until the end of the Earth”

different. A hammer and chisel pound at its rocky bed and the crystal faces its fiercest test. Collected by a human, it is cut on a diamond wheel, probed by an ion beam. The human reads the dates on its atomic clocks, deciphers its long history from its many scars – and, content with the knowledge, throws it away.

Diminished but still resilient, the zircon travels on towards the sea again, and another underground sojourn. Who would bet against it surviving to the end of the Earth?
 Jan Zalasiewicz

A DISTANT GALAXY TWEAKS YOUR DNA

TRAVELLER A cosmic ray
ORIGIN A galaxy far, far away
DESTINATION Our atmosphere
DURATION Billions of years, or weeks

Its nursery is the heart of a supergiant star about to explode into a radiant supernova. At a temperature of about 100 million kelvin, atomic nuclei collide and fuse, adding still more heat to the furnace. Just there on the outer edge of the core is our traveller, a product of that fusion: a nucleus of iron.

The star's core has been growing for a few hundred thousand years. Eventually it gets too big to hold itself together and suddenly collapses, generating a supernova blast of radiation that shreds the entire star. Caught in the explosion, the iron picks up speed, is bounced around by a combination of shock waves and turbulent electromagnetic fields, gains more and more energy as it goes, until finally it breaks out of the fireball and flies free.

This is a gentle beginning. Our iron speeds through space, leaving behind it the dead star's glowing nebula. It is headed for the centre of the galaxy, where a monster awaits: a supermassive black hole, a billion times the mass of our sun. Swept up by a stream of gas, the nucleus is dragged perilously close to the point of no return, where it would be inevitably pulled through the black hole's event horizon to who-knows-what beyond. But at the eleventh hour it is caught by the intense magnetic tornado that circles the black hole, catapulted into a jet of plasma, and squirted out at 90 per cent of the speed of light.

The shock waves in this jet are even more extreme than the ones of the supernova fireball, turning the whole thing into a gigantic, tumultuous particle accelerator. High-energy



A TWINKLE IN YOUR EYE

TRAVELLER Starlight
ORIGIN Cygnus constellation
DESTINATION Your eye
DURATION 1500 years,
 or no time at all

charged particles bounce off tangled magnetic fields, gaining energy as they are batted around. A few are accelerated to colossal energies.

By the time our iron nucleus leaves this maelstrom, it has an energy of about 8 joules, millions of times greater than anything Earth's Large Hadron Collider can produce. Now at about 99.999999999999999999 per cent of the speed of light, it is flung out of its native galaxy into the emptiness of intergalactic space.

As the iron nucleus wanders between galaxies, pulled this way and that by magnetic fields, its view of the universe is a strange one. At this ludicrous speed, the effects of relativity compress faint starlight from all directions into a single point dead ahead. Relativity also does strange things to time. While the nucleus is travelling, the universe around it ages by 200 million years. In another distant galaxy, Earth's sun completes one lazy orbit of the Milky Way, dinosaurs proliferate, continents split and rejoin. But to the speeding iron nucleus, the whole trip takes about 10 weeks.

On the last day of its intergalactic holiday, our traveller finally approaches the Milky Way's messy spiral. It heads towards a type G2 dwarf star, and a planet where the

dinosaurs are now long dead.

According to on-board time, the iron nucleus passes Pluto just 16 microseconds before it reaches Earth. When it arrives here, we call it an ultra-high-energy cosmic ray.

The wispy gases of our upper atmosphere present a barrier far more challenging than anything it has encountered so far. The iron nucleus hits a nucleus of nitrogen, and the extreme energy of the collision not only obliterates both nuclei, but creates a blast of pions and muons and other subatomic particles. Each has enough energy to do the same again to another nucleus, generating a shower of ionising radiation that cascades down through the atmosphere.

Some of these particles will hit an airliner, slightly increasing the radiation dose of passengers and crew. Some may help trigger the formation of water droplets in a cloud – perhaps even help spark a lightning bolt. Some will find their way into living cells, and one will tweak an animal's genes, spurring on the slow march of evolution. But it is very likely that nobody will even notice as the atmosphere scatters the ashes of an exceptional traveller that once flirted with a giant black hole in the faraway Virgo Cluster. Stephen Battersby

In the outer reaches of a star, a photon is born. It is descended from an ancient family, founded tens of thousands of years ago by a nuclear reaction in Deneb's core. Its ancestors bounced off electrons, were absorbed by ions and gradually spawned offspring of lower and lower energy as they meandered outwards from the core.

This photon is lucky: it is created in the star's photosphere, the thin outer layer from which light can escape into space. It is destined to take a longer journey.

Or from the quantum point of view, infinitely many journeys. The path of a photon between its creation and destruction is not precisely defined. Instead, the particle behaves as though it takes all possible paths,

"This infinity of voyages ends in your eye when you look up at the night sky"

with varying degrees of probability. Our photon's wavefunction, describing that probability, spreads out through all of space – but is densest by far along a fairly straight line between Deneb and Earth.

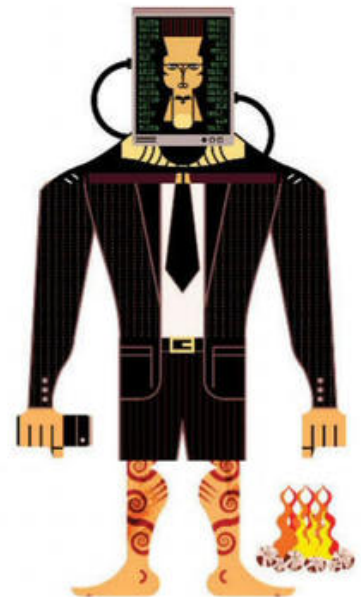
This infinity of voyages ends at the back of your eye when you look up at the clear night sky. The photon hits a blue-sensitive cell in your retina. Its last act is to trigger a nerve that helps you see a bright blue-white point in the constellation of Cygnus – and then it's gone.

By Earthly reckoning the trip has taken between 1500 and 3000 years (the distance from Deneb to Earth is not yet known precisely). It may have begun while Franks and Visigoths were at war, or back when some Phoenician scribe was developing the first alphabet.

But to the photon it lasts no time at all. If you move at the speed of light, time and space shrink to nothing. From this point of view the journey's beginning and end are the same point... in which case you might say that your eye is touching the fiery surface of Deneb, a seething shell of plasma with a temperature of more than 8000 kelvin. Stephen Battersby ■

TRANSFORMERS

Other species are shaped by evolution, but humanity has taken control of its own destiny. So what revolutions made us what we are today – and what will change us in the future?



IT WAS at least 7 million years ago that our ancestors diverged from those of our closest living relatives, the chimpanzees. For most of that time they were apelike forest dwellers, with the furry bodies, small brains and unsophisticated behaviour to match. Then, about 2 million years ago, everything changed. We began to take evolution into our own hands, starting a series of innovations that changed human history – and made us into the very modern apes we are today.

COOKING

Our earliest ancestors may have walked on two legs, but their heads were small, their teeth large and their arms long. No one knows for sure why they began to look more human, but unlike the bodies of other species, which are shaped by natural selection, ours may have been sculpted by our own ingenuity.

Here's the theory. Early hominins dined on tough, raw foods that required a lot of chewing and digesting to break down. That changed when they began to control fire and cook. Heat softens food and breaks down difficult-to-digest fibre into easily absorbed sugars. Big teeth and long guts were no longer necessary, and so over the generations they gradually shrank. Other things shrank too. Because fire wards off predators, our ancestors did not have to retreat to the trees at night and no longer needed such long arms for climbing. Finally, the energy savings made by shrinking body parts went to their heads; their brains began to grow. In other words, *Homo erectus* looked like us because it cooked like us.

Richard Wrangham at Harvard University has been the chief advocate of this hypothesis. "I have not seen any alternative proposals for how *H. erectus* acquired small molars, small guts and terrestrial sleeping," he says. But the idea is not without its problems. Most obviously, while the anatomical changes started some 2 million years ago, the oldest evidence of controlled fire use is just 1 million years old. "I am quite sympathetic to the cooking hypothesis," says Michael Chazan at the University of Toronto in Canada, whose team discovered the ancient deposits of ash and burnt bone in a cave in South Africa in 2011. "But *H. erectus* may have had less complete reliance on cooking [than later species of humans]."

An alternative idea pins brain growth on a shift to eating meat, which would provide a more nutritious diet. It implies *H. erectus* was a skilled hunter. Our bodies certainly seem adapted to chase down prey until it is totally exhausted. But another ancient human innovation reshaped the rules of the hunt – and perhaps the nature of human societies too.

WEAPONS

Projectile weapons travel faster than even the speediest antelope. A study published last year suggested that *H. erectus* made use of them, since it was the earliest of our ancestors with a shoulder suitable for powerful and accurate throwing. What's more, unusual collections of fist-sized rocks at a *H. erectus* site near the town of Dmanisi in Georgia give an idea of their projectile weapon of choice.



RON NICKEL/PLAINPICTURE

How we decorate and adorn ourselves has layers of meaning

But throwing rocks did more than offer a new hunting strategy: it also gave early humans an effective way to kill an adversary. Christopher Boehm at the University of Southern California has suggested that projectile weapons levelled the playing field in early human societies by allowing even the weakest group member to take down a dominant figure without having to resort to hand-to-hand combat. So weapons, he argues, encouraged early human groups to embrace an egalitarian existence unique among primates – one that is still seen in hunter-gatherer societies today.

In fact, weapons may have had an even

greater impact. Paul Bingham and Joanne Souza at Stony Brook University in New York developed the idea that human societies used, and continue to use, the threat of projectile weapons to encourage a high level of cooperation among group members. They call it the social coercion theory.

JEWELLERY AND COSMETICS

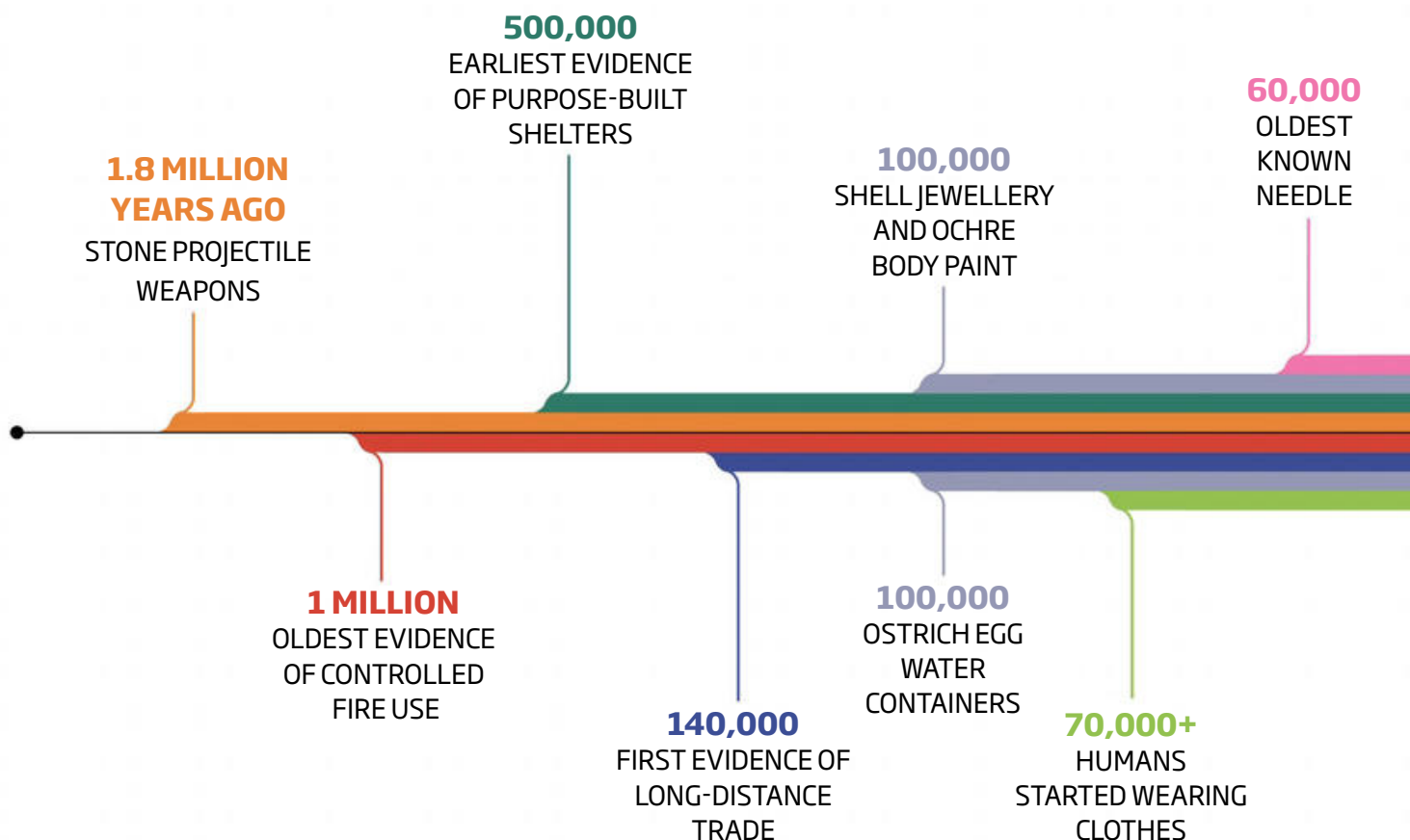
If Bingham and Souza are right, we would recognise some of our social behaviour in *H. erectus*. However, it is not until 100,000 years ago – after the appearance of *Homo sapiens* – that many of our most recognisable habits began to form.

At the Blombos cave in South Africa, excavations a decade ago revealed collections of shells that had been perforated and stained, and then strung together to form necklaces or bracelets. Similar finds have now turned up at other sites in Africa. More recently, work at Blombos has uncovered evidence that ochre was deliberately collected, combined with other ingredients and fashioned into body paint or cosmetics.

At first glance these inventions seem trivial, but they hint at dramatic revolutions in the nature of human beliefs and communication. Jewellery and cosmetics were probably prestigious, suggesting the existence of people of higher and lower status and challenging the egalitarian sensibilities that had existed since the early days of *H. erectus*. More importantly, they are indications of symbolic thought and behaviour because wearing a particular necklace or form of body paint has meaning beyond the apparent. As well as status, it can signify things like group identity or a shared outlook. That generation after generation adorned themselves in this way indicates these people had language complex enough to establish traditions.

SEWING

What people invented to wear with their jewellery and cosmetics was equally revolutionary. Needle-like objects appear in the archaeological record about 60,000 years ago, providing the first evidence of tailoring, but humans had probably already been wearing simple clothes for thousands of years. Evidence for this comes from a rather unusual source. Body lice, which live mostly in clothes, evolved from hair lice sometime after humans began clothing themselves, and a study of ➤



louse genetics suggests body lice arose some 70,000 years ago. A more recent analysis puts their origin as early as 170,000 years ago. Either way, it looks like we were wearing sewn clothes when we migrated from our African cradle some 60,000 years ago and began spreading across the world.

Mark Stoneking at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, an author on the original louse study, suggests that clothes would have allowed humans to inhabit cold areas that their naked predecessors could not tolerate. Sewing could have been a crucial development, since fitted garments are more effective at retaining body heat than loose animal furs. Even then, the frozen north would have been a challenge for a species that evolved on the African savannah, and recent research indicates that we also took advantage of changes in the climate to spread across the world.

CONTAINERS

When some of our ancestors left Africa, they probably travelled with more than just the clothes on their backs. About 100,000 years ago, people in southern Africa began using ostrich eggs as water bottles. Having containers to transport and store vital resources would



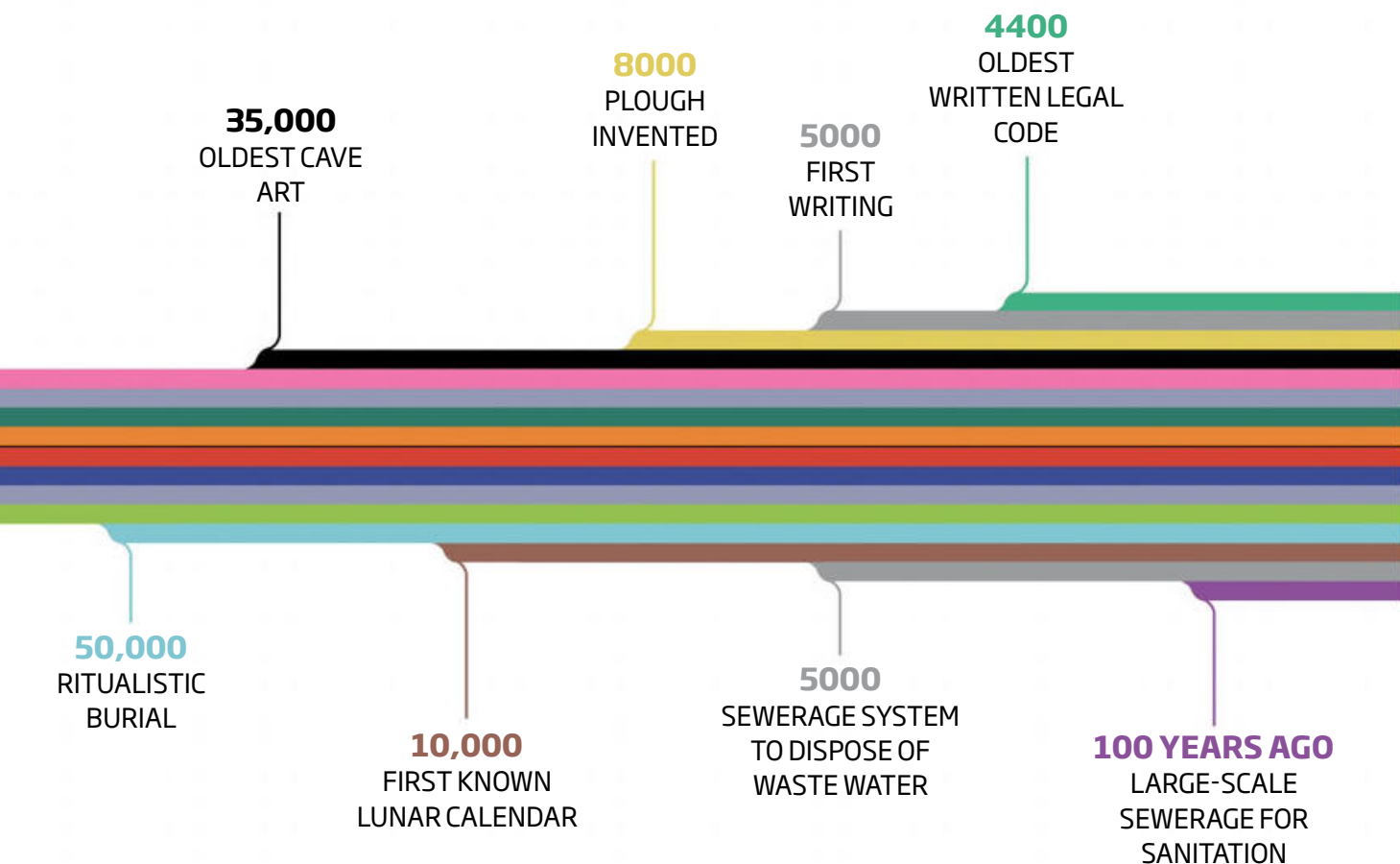
have given them huge advantages over other primates. But engravings on these shells are also highly significant: they appear to be a sign that dispersed groups had begun to connect and trade.

Since 1999, Pierre-Jean Texier at the University of Bordeaux in France has been uncovering engraved ostrich egg fragments at the Diepkloof rock shelter, 150 kilometres north of Cape Town in South Africa. The same five basic motifs are used time and again, over thousands of years, implying they had a meaning that could be read and understood across numerous generations. Texier and his colleagues think they show that people were visually marking and defining their belongings to maintain their group identity as they began travelling further and interacting with other groups.

LAW

As our ancestors began trading, they would have needed to cooperate fairly and peacefully – with not just group members but also strangers from foreign lands. So trade may have provided the impetus to invent law and justice to help keep people in line.

Hints of how law evolved come from modern human groups, which, like Stone Age hunter-gatherers, live in egalitarian,



decentralised societies. The Turkana are nomadic pastoralists in east Africa. Despite having no centralised political power, the men will cooperate with non-family members in a life-threatening venture – stealing livestock from neighbouring peoples, say. While the activity itself may be ethically dubious, the motivation to cooperate reflects ideas that underpin any modern justice system. If men refuse to join these raiding parties they are judged harshly and punished by other group members, says Sarah Mathew at Arizona State University in Tempe. “They display mechanisms of adjudication and punishment akin to formal judiciary, suggesting that law and justice predates the emergence of centralised societies.”

TIMEKEEPING

As trade flourished over the millennia that followed, it wasn’t just material goods that were exchanged. Trade in ideas encouraged new ways of thinking, and perhaps the early stirrings of scientific thought. Communities of hunter-gatherers living in what is now Scotland may have been among the first to scientifically observe and measure their environment. Aberdeenshire has many Mesolithic sites dating from about 10,000 years ago, including an odd monument

consisting of a dozen pits arranged in a shallow arc trending roughly north-east to south-west. When Vincent Gaffney, then at the University of Birmingham, UK, and his colleagues noticed that the arc faced a sharp valley on the horizon through which the sun rises on the winter solstice, they realised it was

“The ideas that transformed us may also have sown the seeds for future revolutions”

a cosmological statement. The 12 pits were almost certainly used to keep track of lunar months. The Aberdeenshire lunar “calendar” – or “time reckoner” as they dubbed it – is comfortably twice the age of any previously found.

“Almost every culture begins to define the passing of time using the moon,” says Gaffney. By establishing a formal concept of time you know when to expect seasonal events, such as the return of salmon to the local rivers. And knowledge is power. “If you have that arcane knowledge you have the opportunity to control society,” says Gaffney.

PLOUGHING

While Scotland’s hunter-gatherers were measuring time, their contemporaries in the Near East had settled down to farm. Crop cultivation is tough work that inspired the first farmers to invent labour-saving devices. The most quintessential of these, the plough, might have influenced society in a surprising way.

In the past, as today, hunter-gatherer societies were probably often divided along gender lines, with men hunting and women gathering. Farming promised greater gender equality, because both sexes could work the land, but the plough – which was heavy and so primarily controlled by men – brought an end to that. So argued Danish agricultural economist Ester Boserup in the 1970s. In 2013 Paola Giuliano at the University of California, Los Angeles, and her colleagues tested the idea by comparing gender equality in societies across the world that either adopted the plough or a different form of agriculture. Not only did they confirm the plough effect, they found that it continues to influence gender perceptions today. “The plough is not the only determinant of differences in gender roles,” stresses Giuliano. “But if two societies are otherwise alike, those that use the plough will be more gender-biased.” ➤

SEWERAGE

Farming has been described as the worst mistake in human history: it is back-breaking work. But it did provide such plentiful food that it allowed the growth of urban centres. City living comes with many advantages but it also carries a health warning; urbanites are at risk from infectious diseases carried by water.

Almost as long as there have been cities, there have been impressive sewerage systems. Cities in the 5000-year-old Indus Valley society were built above extensive drains. Lavatory-like systems existed in early Scottish settlements dating from around the same time, and there are 3500-year-old flush toilets and sewers in Crete.

But none of these were really designed with sanitation in mind, says Thomas Bond at Imperial College London. "Many of the sewerage systems were advanced in a civil engineering sense, but they were really just to dispose of waste water – for example into the nearest river."

It was only in the 1850s, when physician John Snow linked an outbreak of cholera in London to insanitary water supplies, that people started to clean waste water. Large-scale centralised sewage works date from the early decades of the 20th century. Effective sewerage was a long time coming, but when it did arrive it revolutionised public health.

WRITING

The engraved ostrich eggshells of Diepkloof (see page 72) show that modern humans have used graphical symbols to convey meaning for at least 100,000 years. But genuine writing was only invented about 5000 years ago. Now people could record information and pass it between places and generations. Cultural evolution would never be the same again.

Writing also provided a means to convey hopes and fears, revealing how subsequent innovations had affected the human psyche. Some of the world's oldest texts, from the Mesopotamian city-state of Lagash, rail against the spiralling taxes exacted by a corrupt ruling class.

Soon afterwards, King Urukagina of Lagash wrote what is thought to be the first documented legal code. He has gained a reputation as the earliest social reformer, creating laws to limit the excesses of the rich, for instance, but his decrees also entrench the inferior social position of women. One details penalties for adulterous women, but makes no mention of adulterous men. Despite all our revolutionary changes, humanity still had some way to go. **Colin Barras ■**

The next 1000 years

Eternal health, brain uploads, the end of privacy...
What innovations will shape humanity's future?

TWO million years of innovation has changed our bodies, brains and behaviour. An unassuming ape became a species with symbolic thought and sophisticated language. We covered the earth and carved out complex relationships with each other and the natural world. Our inventive ingenuity has allowed us to shield ourselves from the worst of nature's slings and arrows and step beyond the biological constraints of our ancestors.

But it's not going to stop here. As our rate of innovation continues to increase, what we invent will continue to change who we are in ways we can only begin to imagine.

END OF AGEING

Perhaps we will pop pills. Or perhaps doctors will become more like mechanics who we'll visit for regular genetic maintenance. Either way, despite recent research suggesting there is an upper limit on human lifespan, many think we're close to a breakthrough in radically delaying ageing, if not halting it entirely. Some people alive today could live well into their second century. "The nice thing about life extension is that we are already in the middle of this revolution," says Anders Sandberg of the University of Oxford's Future of Humanity Institute.

When death by age-related causes becomes uncommon, accidents and acute diseases will be the big threats and so our environment will probably grow increasingly safe and sanitised. How else will our lives change? For a start, the rhythm of life will be altered. "The seven ages of man will become six, with the first five unchanged and the sixth one extended indefinitely," says gerontologist Aubrey de Grey, co-founder of the SENS Research Foundation in Mountain View, California, which investigates rejuvenation technologies. For the first 50 years or so, life may be similar to today, with milestones like puberty, adolescence and declining fertility. After that, biological changes will be put on hold. "The division into chapters will be delivered not by changes in our health and vitality, but by our own choices, whether in career, relationships or whatever," says de Grey.

Maintaining a sense of identity over so long a life will depend on how far we can stretch our memory, which evolved to cover briefer timescales. Paul Reber at Northwestern University in Evanston, Illinois, is optimistic. "I don't think there's any sense we are going to



"Our lives could be managed by virtual assistants that anticipate our every whim"



PASCALLA/PICTURETANK

hit an information limit,” he says. Childhood memories, especially, seem to get etched in for life. It’s the years between childhood and recent events that sometimes come up blank, but that’s due to bottlenecks in the creation of new memories. “The process is too slow for real life,” says Reber. Recording, or life-logging, systems will no doubt help. We may just need a reboot every now and again, says Sandberg.

Family structure will change too, from nuclear to linear. With not just grandparents, but our grandparents’ grandparents still alive, families will be skewed towards older adults. With older generations supporting us for longer, our youth might extend too – perhaps with a focus on child-rearing earlier on and education later. These linear families could also be more changeable. Will we remain in a relationship with the same person for a century or more? Living alongside people of different ages will expose us to a wider range of experiences and opinions. And long lives

could make people more caring, not just to each other but to things like their environment. “Your decisions will come back to haunt you,” says Sandberg. **Catherine de Lange**

DECISION-MAKING MACHINES

Many of life’s little dilemmas are already dealt with by personalised algorithms. What to read, what to listen to, who to connect with socially. Maps suggest where to go, apps suggest what to do when we get there. As machines get to know us even better, the trend will accelerate. Our lives could be managed by virtual assistants that anticipate our every whim.

Sound like bliss? Perhaps. There is evidence to suggest we will welcome being freed from the tyranny of choice. Making decisions can be cognitively taxing.

Studies have shown that we prefer to choose from a limited number of options and are less satisfied with choices when we know they can be changed. “Not having that worry

is probably going to be beneficial in terms of mental health,” says psychologist Iroise Dumontheil at Birkbeck, University of London.

What will we do to occupy our minds instead? “We’re inherently social,” Dumontheil says. “Parents might play more with their children, couples could have more time together and so on. These social aspects could become more important.”

But Valerie Reyna, a neuroscientist at Cornell University in Ithaca, New York, thinks we shouldn’t be too quick to give over

“Longer lives could make people more caring, not only to each other but to their environment”

decision-making to machines. The experience helps us develop self-control and teaches us how to assess risk, for example. That’s partly why adolescents incarcerated at a young age – and thus prevented from making the same life decisions as their peers – are more likely to act impulsively and commit crimes like shoplifting. In a choice-free future, our lack of learned inhibition might get the better of us.

People’s ability to make choices is fundamental, says Reyna. “If you take that away I think people will feel that they’re missing something and attempt to compensate.” Self-expression could offer one outlet. Manipulating body image, for example, might let people assert a degree of control that is lacking elsewhere. **Chris Baraniuk**

CUSTOMISABLE BODIES

As consumer technology becomes ever more indispensable for day-to-day life, many people may choose to augment their “biological baseline” with implants. The age of customisable humans will have come.

The best place to start examining what this future might look like is with people who society views as disabled or infirm today – ironically exactly those groups excluded by past eugenics movements that aimed to “improve” the human race.

For better or worse, our attempts to treat people with permanent disability often become attempts to recreate their bodies according to a “normal” template. “When you get treatment, you lose your individuality,” says Nigel Ackland, who lost his right hand in an industrial accident. “The doctors



“Human augmentation might lead to an arms race between haves and have-nots”

CRYPTOCURRENCIES

Bitcoin is the most famous cryptocurrency: its technology allows any kind of transaction to be carried out and a public record stored across millions of computers around the world, out of the hands of any centralised authority. The blockchain, as this global ledger is known, enforces fairness and transparency in the exchange of any goods or services. But the legacy of cryptocurrencies will go far beyond money. Some think they are the start of fully autonomous companies trading among themselves - without humans in the loop.

VIRTUAL REALITY

Supplementing or even supplanting the real world's impact on our senses through augmented and virtual reality will let us slip between digital and physical realms seamlessly. We may find new ways to manipulate data and conceptual puzzles by visualising them in a virtual environment. With our senses hijacked, any experience we can dream of will be possible. Or are we already living this dream, as inhabitants of a simulation created by more advanced humans?

BRAIN UPLOADS

Who do you want to be today? As we unravel the brain's structure, some believe we will be able to simulate its function in silicon. If that's possible, many will seek immortality by uploading their minds to a computer. Why stop there? Running our brains digitally may let us load up past versions of ourselves - or “try on” other personalities entirely. We could copy ourselves, living out multiple lives simultaneously. We could even run some of those lives at different speeds, experiencing a lifetime in minutes.

GENETIC ENGINEERING

Future technology will be wetter than it is today, as biological and computer sciences merge. By programming genes, controlling living things as we now control computers, we will grow new types of machine, develop new medicines and even create new organisms. The lines between the worlds of information and matter will blur.

SPACE COLONISATION

If billionaire technologist Elon Musk is right, in a hundred years time a million people will be living on Mars. Most would say that's overoptimistic, but in the long term, the survival of our species depends on our colonising other planets and one day other solar systems. In a few billion years our sun will die and we will be forced to find other homes. This is one innovation that *Homo sapiens* - or whatever our species becomes - cannot live without.

have a one-size-fits-all mentality.”

Some now reject that idea, and see no reason why their prosthesis should look like a natural arm or leg. That's the rationale, for example, behind the Alternative Limb Project, run by prosthetist Sophie de Oliveira Barata in London. Her workshop can make you a jewel-encrusted leg, or a feathered arm.

Where might such a philosophy lead us when the functionality of human prostheses becomes a playground and prostheses, whether artificial limbs or brain chips, become enhancements? Once we can build an arm that is as good as a human one, why stop there? Why shouldn't you have one twice as strong, or three times as fast?

“Every prosthetic limb should have something a human limb can't do,” says Ackland, who now uses an advanced bionic hand (pictured below). “When I rotate my wrist 360 degrees, people are blown away. They don't see the fact I'll never play piano, or be a speed typist, or feel my wife touch my hand. They see me do something they can't. It's a tiny thing, but I can stand a little straighter. It makes me feel like an individual again.”

There are concerns that this kind of human augmentation will lead to an arms race between the haves and have-nots, leaving behind those who cannot or will not adapt. This fear is not entirely without grounds. Literacy is both a technology and a widespread human augmentation, for example. It raised the bar of what we expect a person to be able to do, and illiteracy in modern society goes hand-in-hand with disenfranchisement.

But the advent of mass literacy was also a mass democratisation of ideas. Similarly, greater human augmentation could see a greater diversity in what it means to be human. **Frank Swain**

END OF PRIVACY

The old boundaries of privacy have shifted. The more technology has allowed us to share, the more we've embraced it. Social media brings out confessions, while photo and video sites are awash with candid self-promotion. We can even adorn ourselves with gadgets that publicly display our emotions. Soon, we could be reading off the histories and proclivities of people we meet via pop-ups on augmented-reality displays. The veil between our private and public lives is growing thin.

Many respond by proactively managing their online presence. On his website Andrew Hodges, a mathematician and biographer of Alan Turing, gives his personal and professional lives an equal footing. Hodges's online openness about his homosexuality is there to make a political point: “Everything is connected with everything else.”

But while not having secrets can be liberating, it is getting harder to control the flow of information. Share your likes on Facebook, for example, and you reveal things about yourself you might not even know. Do you like curly fries? Then you're a measurable number of IQ points brighter than the population at large. Other jarring correlations predict sexual preference and political affiliation. Michal Kosinski, who led the study showing these correlations while at the University of Cambridge, has designed systems that mine online trivia for personality traits, helping recruiting agencies identify suitable applicants. “It's a great commercial prospect, as long as it is used ethically,” says Kosinski, now at Stanford University. But ethics moves with the times. The photos you post today will be analysed by the algorithms of tomorrow. What might they reveal then?

And more is coming all the time. We are



Future prostheses will explode the limits of the human body

FADEICHEV/SERGE/ITAR-TASS PHOTO/CORBIS

flooding the world with surveillance technologies to the point where everyone sees everyone. Cameras already capture – and share – everything, from the conduct of state power at public protests to the contents of politicians' pyjamas. In a world of "sousveillance", where everyone carries monitoring devices, the truth will out.

There is some evidence to suggest an open society will be a better one, but openness does not equal freedom. In China, "big mammas" work quite openly to remove politically sensitive postings from internet bulletin boards. And

in East Germany, at the height of the cold war, 1 in 63 people was a state informant. In a global village, there will be gossips. **Simon Ings**

AN ABUNDANCE OF EVERYTHING

If we get things right, we're heading for a future of abundance. Used materials will be recycled by 3D printers that churn out everything from consumer electronics and building supplies to food and synthetic organs. Advances in molecular engineering will let us make anything out of anything, remoulding the molecules

of one material into another. We'll have everything we need, and want for nothing.

Or will we? "Once we have the ability to print whatever we want, things will become customisable ad nauseam," says Stuart Armstrong of the University of Oxford's Future of Humanity Institute. "Creativity will be more valuable than manufactured goods." We may also come to value old things over the new, as antiques become increasingly rare in a world of super-efficient recycling.

In such a future our ties with the natural world are likely to loosen further. If meat and vegetable matter can be produced synthetically, agriculture will disappear. Will we then shun or embrace rural spaces? Present trends suggest that rather than isolating us from the environment, technology can bring us closer to it. "Biodiversity and ecosystems are not a

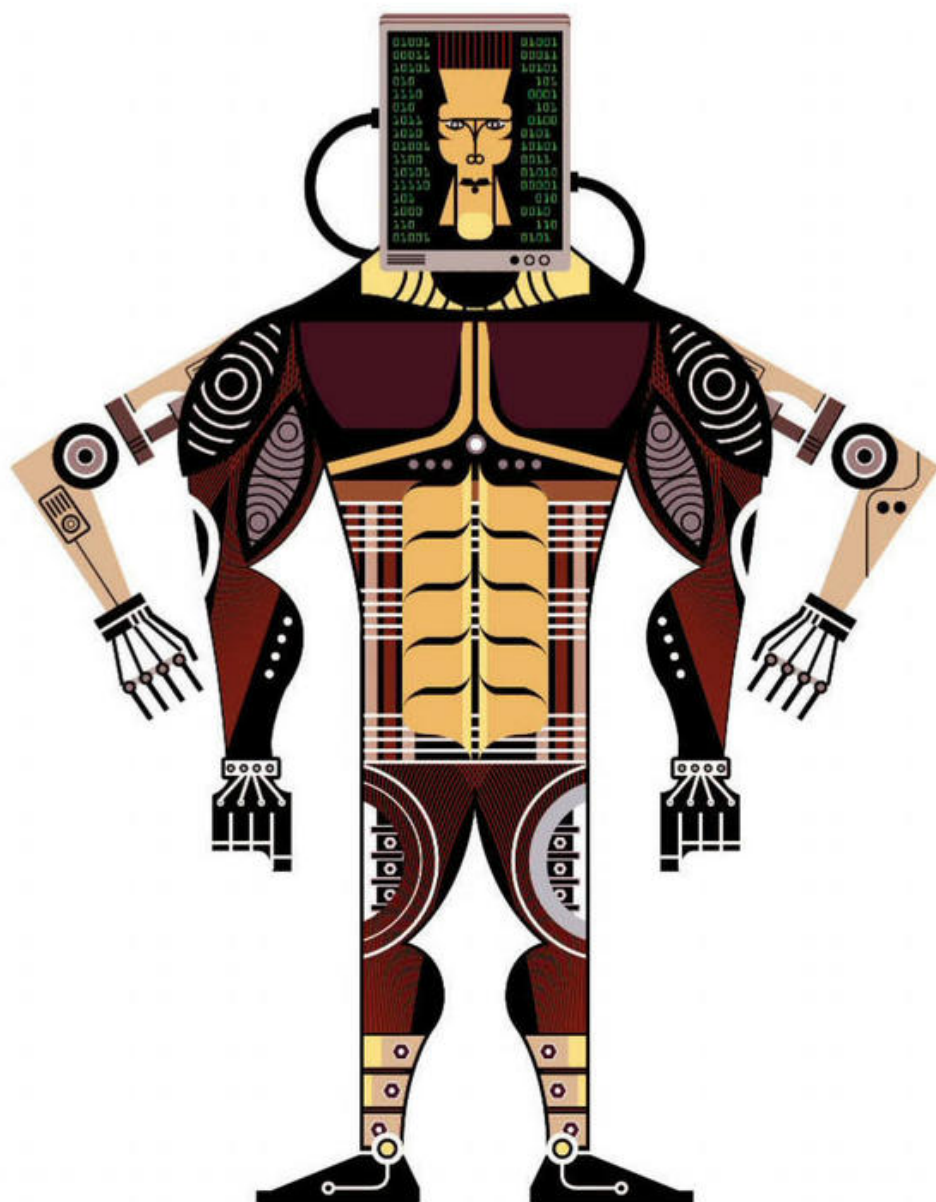
"In a world where everyone carries monitoring devices, the truth will out"

fad," says Ben Novak of the Long Now Foundation based in San Francisco.

Richer countries today have the luxury of putting more emphasis on conservation, and visits to national parks and reserves are generally on the rise. "The majority of human beings have a general curiosity and awe for at least some form of nature," says Novak. "People want to be immersed in it." Vast tracts of reclaimed farmland may be set aside for wildlife.

Some of that wildlife may be revived. De-extinction projects are under way to resurrect the passenger pigeon, dodo and many other species. "The biggest reason we want to conserve biodiversity is that it represents the universe's most complex and extensive source of information, the most interesting puzzles to solve," says Novak.

All that won't necessarily make us happier. "One part of the human condition is dissatisfaction – in a sense, this is what drives technological advances," says Ian Tattersall, a palaeoanthropologist at the American Museum of Natural History in New York. Even if we could have anything we want, we won't stop wanting what we don't yet have. "No matter how much you modify the external environment, our species' nature is not going to change enormously," he says. "That's the curse of our imagination." **Rachel Nuwer** ■



The big freeze

A peek inside a groundbreaking
cryogenic centre leads **Helen Thomson**
to investigate how it could
revolutionise health

“WE’RE taking people to the future!” says architect Stephen Valentine, as we drive through two gigantic gates into a massive plot of land in the middle of the sleepy, unassuming town that is Comfort, Texas. The scene from here is surreal. A lake with a newly restored wooden gazebo sits empty, waiting to be filled. A pregnant zebra strolls across a nearby field. And out in the distance some men in cowboy hats are starting to clear a huge area of shrubland. Soon the first few bricks will be laid here, marking the start of a scientific endeavour like no other.

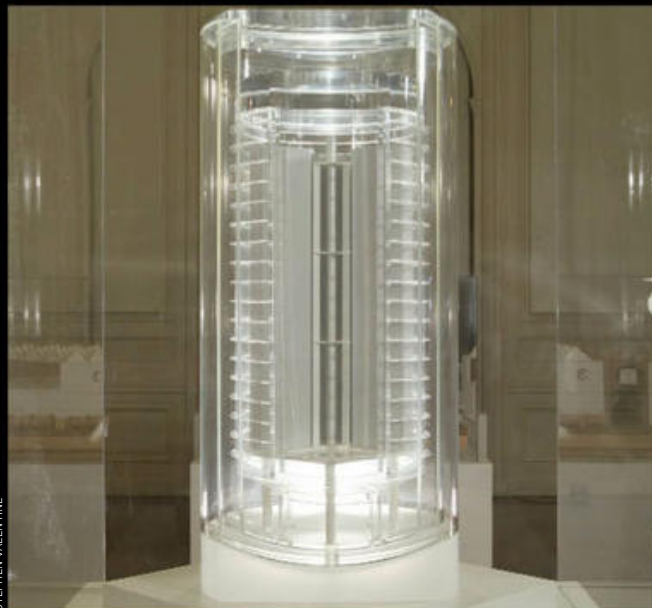
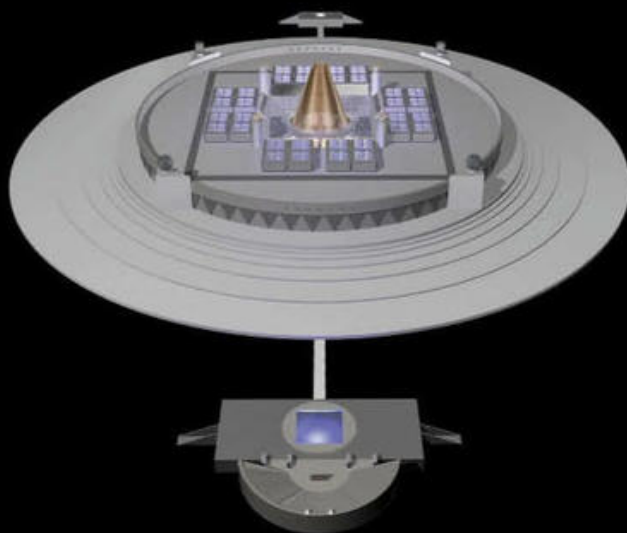
After years of searching, Valentine chose this site as the unlikely home of the new Mecca of cryogenics. Called Timeship, the monolithic building will become the world’s largest structure devoted to cryopreservation, and will be home to thousands of people who are neither dead nor alive, frozen in time in the hope that one day technology will be able to bring them back to life. And in May, building work began.

Cryonics, the cooling of humans in the hope of reanimating them later, has a reputation as a vanity project for those who have more money than sense, but this “centre for immortality” is designed to be about much more than that. As well as bodies, it will store cells, tissues and organs, in a bid to drive forward the capabilities of cryogenics, the study of extremely low temperatures that has, in the last few years, made remarkable inroads in areas of science that affect us all: fertility therapy, organ transplantation and emergency medicine. What’s more, the cutting-edge facilities being built here should break through the limitations of current cryopreservation, making it more likely that tissues – and whole bodies – can be successfully defrosted in the future.

Timeship is the brainchild of Bill Faloony and Saul Kent, two entrepreneurs and prominent proponents of life extension research. Their vision was to create a building that would house research laboratories, DNA from near-extinct species, the world’s largest human organ biobank, and 50,000 cryogenically frozen bodies. Kent called it “all part of a plan to conquer ageing and death”.

In 1997, Kent asked Valentine, an architect based in New York, whether he could design a building that was stable enough to operate continuously for 100 years with minimal human input. It needed to withstand earthquakes, to be protected from natural disasters and acts of violence, and to survive without the mains power supply for months on end. It was a list of demands that no building in the world currently satisfies. ➤

Above: computer renderings of the Timeship project. Right: conceptual model of the Temperature Control Vessels that will store bodies and tissues



STEPHEN VALENTINE

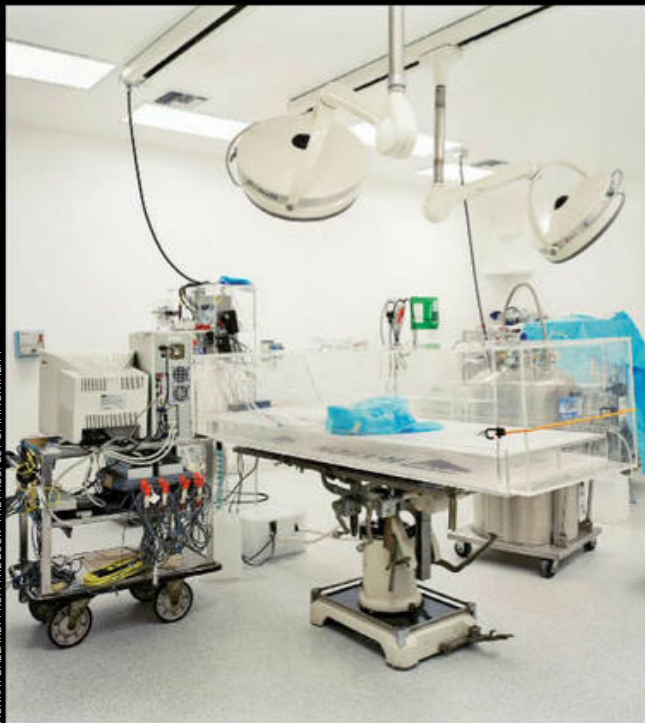
WHAT HAPPENS WHEN YOU ARE FROZEN?

Cormac Seachoy, a graduate from Bristol, UK, was just 27 when his body succumbed to metastatic cancer of the colon. He was pronounced dead on 16 December last year. Not long after, he became Alcor's 142nd cryopreserved member. Seachoy, who had decided he wanted to be frozen after death, had planned to relocate to Scottsdale, Arizona, to be close to Alcor's main facility, but his condition went downhill too fast. "Ideally, we are there at the bedside so that we can take over within 60 seconds of the patient being pronounced dead," says Aaron Drake, head of Alcor's medical response team. Instead, Drake made the journey to the UK but was still in the air when Seachoy passed away. An organisation called Cryonics UK stepped in, cooling the body and administering the first lot of drugs until Drake and his team arrived. "As soon as death is pronounced, we want to mitigate as much from happening in the cells as possible," says Drake. To do that, his team restores blood circulation using a pump to mechanically do chest compressions and intubates the patient to restore oxygen to the lungs. "We can do bloods at this point to show they are every bit as normal as a living patient, biologically speaking," he says.

Next, the team reduces the rate of metabolism to slow decay. "We immerse the patient in an ice bath and circulate chilled water that draws heat away from the body," says Drake. "We then administer drugs that are designed to prevent clots from forming, break up existing clots and keep a good pH balance and blood pressure. And a general anaesthetic acts to reduce metabolic activity in the brain."

The next step is to replace all the blood in the body with medical-grade antifreeze. "We are trying to prevent any ice from forming when we take the body below freezing point," says Drake. "We continue to cool the body and eventually everything turns into a glass-like solid."

Seachoy's body was held in this state using dry ice, and flown to Alcor to be stored along with Alcor's other members in liquid nitrogen at -196°C . Here he will remain, possibly for hundreds or thousands of years, waiting for the day that technology can treat the cancer and bring him back to life. "We can't promise that they'll be able to be resuscitated some day," says Drake. "That will depend on future technologies - but if we've been successful and started the process within seconds of clinical death, we've been able to mitigate all types of cellular damage."



MURRAY/BALLARD, FROM THE BOOK 'THE PROSPECT OF IMMORTALITY'

Valentine spent months drawing up proposals for the building, together with advice from engineers who had previously worked for NASA and from security experts around the world. "We had to address everything from pandemics and cyberattacks to snipers and global warming," says Fred Waterman, a risk mitigation expert on the Timeship team. The designs were approved by Kent but immediately put on ice. He believed the technology that would make the building worthwhile was not yet advanced enough to warrant its construction.

At body temperature, cells need a constant supply of oxygen. Without it they start to die and tissues decay. At low temperatures, cells need less oxygen because the chemical activity of metabolism slows down. At very low temperatures, metabolism stops altogether. The problem faced when trying to preserve human tissue by freezing it is that water in the tissue forms ice and causes damage. The trick is to replace the water with cryoprotectants, essentially antifreeze, which prevent ice from forming. This works well for small, uncomplicated structures like sperm and eggs. But when you try to scale it up to larger organs, damage still occurs.

But in 2000, Greg Fahy, a cryobiologist at 21st Century Medicine in Fontana, California, made a breakthrough with a technique called vitrification. It involves adding cryoprotectants, then rapidly cooling an organ to prevent any freezing; instead the tissue turns into a glass-like state. Fahy later showed that you could vitrify a whole rabbit kidney that functioned well after thawing and transplantation. This was the breakthrough Kent and Faloon had been waiting for.

Cold comfort farm

The pair gave Valentine a multimillion-dollar budget and told him to find land on which to build Timeship. Valentine spent five years scouring the US, believing it to be the country most likely to remain politically stable for the next 100 years. He homed in on four states that fitted his exacting criteria. And after evaluating more than 200 sites in Texas alone, Valentine ended up in Comfort. Here he discovered the Bildarth Estate, which came with acres of land, a 1670-square-metre mansion and even a few zebras.

Since then, Valentine, together with a team of specialists, has fine-tuned the project. Timeship's architectural plans make it look like something between a fortress and a spaceship. The central building is a low-lying square with a single entrance. This sits inside

The operating theatre at Alcor, where new members are prepared for storage

"THERE'S AN URGENT NEED TO BE ABLE TO STORE WHOLE ORGANS FOR LONGER"



MURRAY BALLARD

be cryopreserving some bone marrow for future tissue to fix my tennis injuries." Lowdell will soon do the first transplant of a tissue-engineered larynx created from a donor larynx that has been seeded with cryopreserved stem cells to reduce the risk of rejection.

Then there's the problem of organ shortage. In the US, there were almost 31,000 transplants carried out in 2015, but at least six times as many people are on the waiting list; each day 12 people die before they can get a kidney. To make matters worse, many organs go to waste because their shelf life is too short to find a well-matched patient. Nearly 500 kidneys went unused in the US last year because the recipient couldn't get the organ in time.

So there's an urgent need to be able to store whole organs for longer. The issue is so important that the US government has pledged to start funding research into this very area. We can already reversibly cryopreserve small bundles of cells – many thousands of babies have been born from vitrified human embryos. Doing the same with large organs, like kidneys or hearts, is harder, but not impossible. Over the past decade, for instance, several babies have been born from ovarian tissue that was removed before chemotherapy, cryopreserved and later replaced. Similarly, rabbit kidneys and rat limbs have been cryopreserved, thawed and placed in a new body. Fahy says his team is well on its way to the first human trial of a cryogenically frozen organ. "After decades of research, we're now at a tipping point," he says. Having improved both the vitrification technique and the cryoprotectant solution, they are moving to trials in pigs, and human trials could follow within five years, he says.

That might help prevent wastage, but we would still have a shortage of organs for transplant. Another solution is to grow them from scratch using our own stem cells, and keep them until we need them. So far, tiny 3D heart-like organs have been made from stem cells alone, as well as mini kidneys and livers, all with the ultimate aim of bioengineering replacement organs for transplantation.

Once organs can be produced like this, we will need a way of storing either the raw material or the organs themselves. "I'm not enthusiastic about the notion of freezing whole heads, but I can certainly imagine people needing to freeze cells, or 'starter kits' for the development of tissues, or even whole organs – and in the not-so-distant future," says Arthur Caplan, a bioethicist at New York University Langone Medical Center.

Like Caplan, most scientists I spoke to said

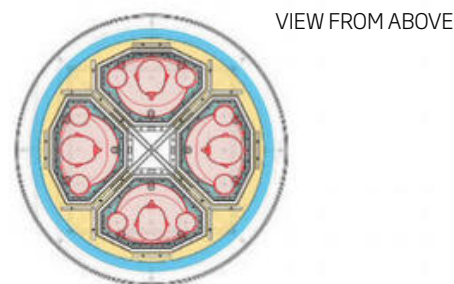
it was becoming more likely that we could bring individual cryopreserved organs back to life, but were less convinced by the idea of freezing whole bodies. So I decided to visit Alcor Life Extension Foundation – the world's biggest cryonics facility – in Scottsdale, Arizona, to find out what happens when a body is put on ice.

Alcor's lobby has the feel of a doctor's waiting room, except that lining the walls are portraits of men, women, children and the occasional dog. The people in the pictures are preserved there, some alongside their beloved pets.

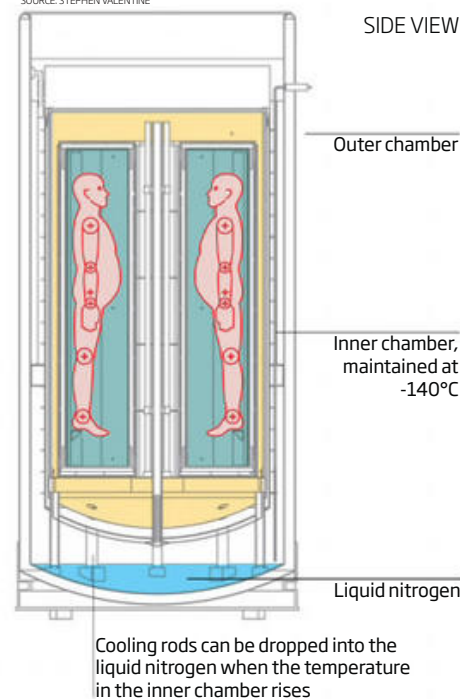
Aaron Drake, head of Alcor's medical response team, says the company has more ➤

Cool design

Cryopreservation typically happens at -196°C using liquid nitrogen, but this can damage tissue. A new storage system called the Temperature Control Vessel works like a self-cooling thermos. It keeps the body at -140°C to reduce damage



SOURCE: STEPHEN VALENTINE



Old-style body vats: time for an upgrade?

a circular wall surrounded by concentric concrete rings. Inside are what Valentine calls "neighbourhoods", collections of thermos-like dewars that will store the cryopreserved DNA, organs and bodies (see diagram, right).

Parts of the project are somewhat theatrical – backup liquid nitrogen storage tanks are covered overhead by a glass-floored plaza on which you can walk surrounded by a fine mist of clouds. Others are purely functional, like the three wind turbines that will provide year-round back-up energy.

The question is, do we need Timeship? Such an extravagant endeavour might not be vital, but it looks as if something similar will be necessary sooner or later. In fact, the strongest argument for such a facility, and the technological developments it promises, might have nothing to do with the desire to be frozen for the future.

We already have small biobanks for storing bones from human donors, as well as tendons, ligaments and stem cells. But with rapid advances in regenerative medicine, there is a growing need for large-scale facilities in which we can store more cryogenically frozen biological material.

Stem cells, for instance, are increasingly cryopreserved after being extracted and grown outside the body for use in regenerative therapies. "Beyond the age of 50, it's harder to isolate stem cells for regenerative medicine," says Mark Lowdell at University College London. "If I were in my 30s, I would certainly

WHAT IS DEATH?

Death has been redefined several times over the past century. It was once considered the cessation of a heartbeat and breathing. Today it includes other scenarios, such as the cessation of brain activity. But even that's not good enough for some.

"Death is a process, not a switch," says Max More, president and CEO of the Alcor Life Extension Foundation in Scottsdale, Arizona. "If you go back 100 years and someone falls over in the street and stops breathing, doctors would say 'this person is dead'. Today we can do CPR and defibrillation to restart their heart and they can be brought back to life. So when that doctor declared them dead, were they? With today's standards, no they weren't." Instead, says More, what we're really saying is "given today's technology and the medicine I have available to me right now, there's nothing more I can do for you".

A definition that emerged in the 1990s in response to this problem is the information-theoretic definition of death. This states that a person is dead only when the structures that encode memory and personality are so disrupted that it is no longer possible in principle to restore them.

Therefore a person who is cryogenically frozen, with brain structures preserved in a state close to what they were before the pronouncement of clinical death, is not by this definition, actually dead. So if the people frozen at Alcor aren't dead, what are they? "There's no good word for what they are," says More. "Some people say they are de-animated."

than 1000 clients signed up worldwide; 99 per cent are healthy, but 1 per cent have a terminal disease. Some of them want to freeze their whole body, others – known as "neuros" – opt for just the head.

Drake admits that the techniques his firm uses aren't perfect, which is why they continue to research the process. Recently, Alcor scientists placed acoustical devices on the brains of neuros as they were lowered into liquid nitrogen, listening as the heads cooled to -196 °C. The colder they got, the more frequently the team heard acoustical anomalies, which they attribute to micro-fracturing of the tissue. "That's damage happening," says Drake. It's difficult to say what effects this might have. "It's not universal or consistent, but it's something we know doesn't happen at around -140 °C."

The problem is, to store a person at -140 °C, you have to keep them warmer than nitrogen's boiling point, which is incredibly hard to do – certainly much harder than placing a body in a giant thermos full of liquid nitrogen, letting it boil and occasionally topping it up.

But at Timeship, Valentine thinks he has cracked the problem. After years of experimentation, he has designed a system called a Temperature Control Vessel (TCV), a dewar that houses cryogenically preserved bodies, heads or tissues. Inside the dewar are moving rods that can be dipped into a pool of liquid nitrogen whenever a sensor notes that the temperature has risen from -140 °C. This would provide a relatively autonomous way

of maintaining the contents at an ideal temperature (see "Cool design", page 81).

Each TCV can carry hundreds of samples of tissue and organs, or four bodies and five heads. They are designed to be stacked together in a tessellating pattern that forms the neighbourhoods within the main building.

This should reduce some of the damage to brain tissue that the Alcor team heard. But even with that technology, is there any hope of reanimating a brain?

Facing the future: portraits of people preserved at Alcor watch over the "animated" living



MURRAY BALLARD

There is some evidence to suggest that certain properties of the mind – memories, for instance – can survive cryopreservation. In 2015, researchers trained worms to recognise a smell, then froze them. On thawing, the worms retained the smell memories.

And this year, Fahy's team cryopreserved a rabbit brain in a near-perfect state. Although the group used a chemical fixative that is not yet used in human preservation, the thawed rabbit brain appeared "uniformly excellent" when it was examined afterwards using electron microscopy.

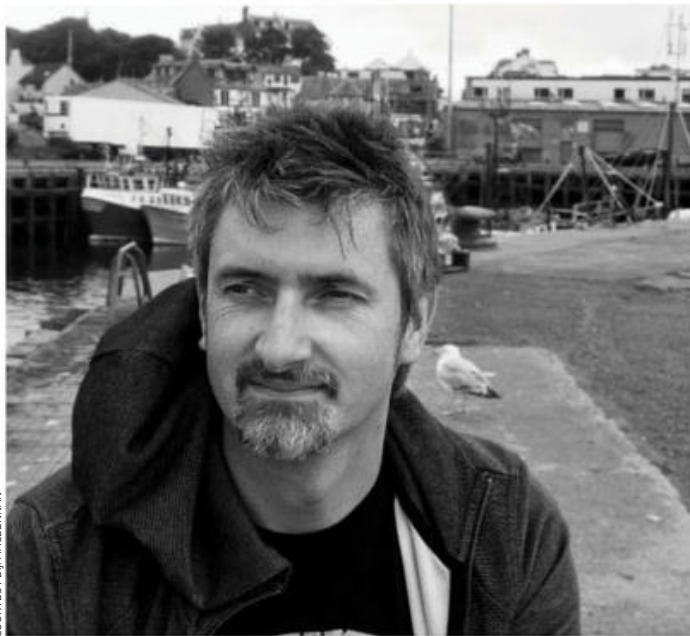
"These kinds of experiments show that it's not such a massive leap of faith to think that we could preserve the human mind," says Max More, president and CEO of Alcor. But not everyone is convinced. Even if you could preserve the delicate structures of the human brain, the cryoprotectants themselves are toxic. "No matter how smart scientists are in the future, you can't change mush into a functional brain," says Caplan, "and I just don't think that what we're able to do right now to preserve the brain is good enough to ever bring it back to life."

There are precedents for the idea that the human brain can be revived after being cooled, however. In 1986, two-and-a-half-year-old Michelle Funk fell into an icy creek where she was submerged for just over an hour. Despite showing no signs of life, doctors spent 2 hours warming her blood through a heart-lung machine. Eventually, she recovered fully. Her doctors figured that the sudden cooling of her brain must have slowed the organ's need for oxygen, staving off brain damage.

Funk's recovery was so remarkable it spurred researchers to repeat the scenario experimentally in pigs and dogs – cryopreserving them for hours before bringing them back to life. The same procedure is now being tested in humans in a groundbreaking trial by surgeons at UPMC Presbyterian Hospital in Pittsburgh, Pennsylvania. There they are placing patients in suspended animation for a few hours, to buy time to fix injuries that would otherwise be lethal, such as gunshot wounds. The technique involves replacing the person's blood with a cold saline solution and cooling the body. They will then try to fix the injuries and bring the patient back to life by slowly warming the body with blood.

That's not so different from what goes on at Alcor, says More. "What we're doing is trying to stretch the time in which the person is suspended. It's just an extension of emergency medicine." I ask More whether he really believes that his members will be brought

"WHAT WE ARE DOING IS JUST AN EXTENSION OF
EMERGENCY MEDICINE - WE ARE STRETCHING TIME"



COURTESY D.J. MACLENNAN

Head start: D.J. MacLennan pays £50 a month to get his head frozen after death

back to life. "I don't know if it will ever happen," he says, "but we're breaking no laws of physics here. Who is to say that in 100 years we won't have the medical tools – some kind of nanotechnology perhaps – that can fix cells at an individual level and repair what's necessary to revive someone in good health."

This is the central argument in favour of cryonics – the possibility, no matter how slim, that it offers a chance of survival. "We think of cryonics as a scientific experiment," says More. "People that are buried or cremated are our control group, and so far, everyone in the control group has died."

Facing the future

It is an expensive experiment, however. Cryopreserving your body will set you back up to \$220,000, payable on death – often via life insurance, with Alcor as the beneficiary.

"People often say that the money would be better spent on family or given to charity," says Ole Moen, a philosopher and ethicist at the University of Oslo, Norway.

"But what's strange about this is that nobody complains when people spend money on expensive cancer treatments or long-term care – people drain the public healthcare budget trying to stay alive all the time," he says. "So why complain when people want to spend their own money trying to live longer via cryonics?"

If you're happy to fork out, there's the big question of what kind of future you'd wake up to. "Even if you could get this technique up and running by some magical future science I believe you'd be a freak – you'd be so far out of it culturally, so lost, that you'd be at risk of being driven mad," Caplan says.

With so many big unknowns, I leave Alcor and Timeship undecided on the utility of cryonics. What's clear, though, is that the underlying research into cryopreservation is worthwhile. Whether it's to help me have children, fix a future tennis injury or potentially even provide me with a new heart, I'd be first in line to freeze cells and tissues today that might help my future self live longer, and healthier.

On my way out of Alcor, I ask Drake whether he wants to be frozen, given that he has cryopreserved so many others. "Yes," he says. "Not because I want to be immortal, I don't think that's possible. I just want to see if all this work was futile. I was the last person these people saw before they took their last breath. Will they see me again? Will they thank me? I don't know if that will ever happen. But wouldn't that be nice?" ■

WHY I SIGNED UP TO GET MY HEAD FROZEN

Taking out insurance to freeze your head after you die is the responsible thing to do, says D.J. MacLennan

Ever since I learned that people eventually died, I have had this fear of death churning away in the background. As a child I was always thinking, "isn't there something we can do about this?"

I considered cryopreservation for many years and then signed up as a neuro in 2007, which means I'll only have my head preserved. It made perfect sense to me that the mind arises as an emergent property of the brain and that it might be possible to preserve that.

I don't know whether it will be possible to bring someone back because it's hard to know what kind of repair work you would have to do to correct any deterioration. So I don't think of how it might work, but of what kind of values might be around at the time.

When you sign up, there's a fair bit of legal paperwork and the finances to sort out. I pay for mine through a life insurance policy that pays Alcor upon my death.

It's about £50 a month.

I discussed it with my wife for several years, but didn't tell anyone else until I'd signed up.

I don't think we should rest on our laurels and be satisfied with our lot. How do we know that we should be happy with this amount of life?

Imagine the regret in the future if this is something that works out and we realise we've got all these people that we've lost that we could have saved?

I don't agree with people who say it's unethical. Where's the wisdom in losing the accrued knowledge of someone who's lived for decades? I think death is a terrible thing. Giving yourself the option, however minute, of keeping hold of all that knowledge and experience is surely the responsible thing to do.

D.J. MacLennan is the author of *Frozen To Life: A personal mortality experiment*





HUMAN UNIVERSE

On Earth, we rule the roost: *Homo sapiens* is the planet's most intelligent, influential and destructive species. We are so dominant that we are considering naming an entire geological epoch after ourselves, the Anthropocene.

But there's a whole universe out there. How do we measure up by that cosmic yardstick?

Are we really the only intelligence? What, if anything, does the rest of the universe know about us? Could we, or should we, spread to other planets? What, if anything, will our lasting legacy be? Over the next 8 pages we explore humanity's place in the universe.

- 1 Was the universe made for us?
- 2 Does consciousness create reality?
- 3 Can we understand everything?
- 4 Could we destroy the universe?
- 5 Does the cosmos know we're here?
- 6 Could we colonise the stars?
- 7 Can we engineer the universe?
- 8 Could we become gods?



1 WAS THE UNIVERSE MADE FOR US?

For much of our existence on Earth, we humans thought of ourselves as a pretty big deal. Then along came science and taught us how utterly insignificant we are. We aren't the centre of the universe. We aren't special. We are just a species of ape living on a smallish planet orbiting an unremarkable star in one galaxy among billions in a universe that had been around for 13.8 billion years without us.

But maybe we were too hasty to write ourselves off. There is a sense in which we are still the centre of the universe.

Science also teaches us that the laws of physics are ridiculously, almost unbelievably, "fine-tuned" for you and me. Take the electromagnetic force. It has a value that is perfectly set for getting stars to bind protons and neutron to create carbon – the building block of life as we know it. Or the strong nuclear force, which binds the insides of protons and neutrons. If it were even a tiny bit stronger, the whole world would be made of hydrogen; if it were weaker, there would be no hydrogen at all. In either case, life as we know it wouldn't be possible. Even the amount of energy contained in empty space seems perfectly set to allow intelligent life to flourish. That's not all. All told, about 12 parameters have been identified as being just right for life.

Why is the universe so perfect? Most physicists now argue that in some sense, it could not have been otherwise. That reasoning has given rise to several different answers known as "anthropic principles".

One end of the spectrum puts us truly back in the centre. This extreme anthropic principle posits that the universe is so perfect that it must have been made for us, either by an intelligent creator or, more likely, because of some fundamental feature of the cosmos that drives it towards intelligent life. In his book *The Goldilocks Enigma*, Paul Davies, a cosmologist at Arizona State University, tentatively suggests the possibility that life could be a law of nature. He calls it the "life principle", although he admits it is verging on the theological.

Most physicists have no time for ideas like this. "To say that this is all for us? That is just completely bizarre," says Sean Carroll, a cosmologist at the California Institute of Technology in Pasadena.

Perhaps, then, it is the other way round: according to another formulation of the anthropic principle, the universe only exists because we do. We conjure it up with our consciousness (see right).

Some less mind-bending versions of the principle are also available. They try to explain why the universe would appear perfectly made for us, even if it isn't. In a nutshell, this weak anthropic principle says that given that we are around to observe the universe, it simply has to allow for our existence.

This is often taken to imply that there are other regions of the universe – or even other universes – where physical laws and constants are different. So asking why things are this way amounts to asking why we are in this region. In that case, the anthropic principle is merely pointing out that places that are hospitable to our kind of life are the only places we can possibly be.

This line of reasoning has been bolstered by the possible existence of a multiverse, versions of which emerge from both quantum mechanics and standard cosmology. With lots of other universes, each with their own physical constants and laws, the mystery of our own fine-tuned universe evaporates. We can only be in one that is fine-tuned for carbon-based life.

But even if this version of the anthropic principle explains fine-tuning, it still restores us to some of our former (self-appointed) glory by putting human observers firmly back into our description of the cosmos. "If you want to explain the universe that we see, the very fact that we are seeing it is part of that explanation," says Davies. "It is a bit of a U-turn in the history of science that has been removing the observer from the picture altogether." Welcome back.

Michael Slezak



SAM CHIVERS



2

DOES CONSCIOUSNESS CREATE REALITY?

Samuel Johnson thought the idea was so preposterous that kicking a rock was enough to silence discussion. "I refute it thus," he cried as his foot rebounded from reality. Had he known about quantum mechanics, he might have spared himself the stubbed toe.

Johnson was responding to Bishop Berkeley, a philosopher who argued that the world was a figment of our minds. Could he have been right?

With its multiverses and cats both alive and dead, quantum mechanics is certainly weird. But some physicists have proposed that reality is even stranger: the universe only becomes real when we look at it.

This version of the anthropic principle (see left) - known as the participatory universe - was first put forward by John Archibald Wheeler, a heavyweight of 20th-century physics. He likened what we call reality to an elaborate papier mâché construction supported by a few iron posts. When we make a quantum measurement, we hammer one of those posts into the ground. Everything else is imagination and theory.

For Wheeler, however, making a quantum measurement not only gives us an objective fix on things but changes the course of the universe by forcing a single outcome from many possibles. In the double-slit experiment (see "Where does quantum weirdness end?", page 49), for example, light is observed to behave either as a particle or a wave, depending on the set-up. The most baffling thing is that photons seem to "know" how and when to switch. But this assumes a photon has a physical form before we observe it. Wheeler asked: what if it doesn't? What if it takes one only when we look?

Even the past may not yet be fixed. Wheeler proposed a cosmic version of

the double-slit experiment, in which light from a quasar a billion light years away reaches us by passing around a galaxy that distorts its path, producing two images, one on either side of the galaxy. By pointing a telescope at each, observers would see photons travelling one of two routes as particles. But by arranging mirrors so photons from both routes hit a detector at the same time, they would see light arrive as a wave. This time, the act of observation reaches across time to change the nature of the light leaving the quasar a billion years ago. For Wheeler, this meant the universe couldn't really exist in any physical sense - even in the past - until we measure it. And what we do in the present affects what happened in the past - in principle, all the way back to the origins of the universe. If he is right, then to all intents and purposes the universe didn't exist until we and other conscious entities started observing it.

Sound crazy? Then try this one on for size. Another interpretation of quantum mechanics is Hugh Everett's many worlds hypothesis, which posits that everything that could happen has and does, in an infinite number of universes. Every time you make a decision, the universe splits in two, with you in one branch and an alternative you in the other, living the other possibility. The universe you occupy is, in some sense, an individual universe of your own making.

This idea is enough to give anyone a reality check. "My natural inclination is to be a realist," says Chris Timpson, a philosopher of physics at the University of Oxford. "But if you're going to be a realist about the quantum world, then you're left with a world that's very peculiar." So peculiar, in fact, that the idea that it only exists because of us seems almost sensible.

Douglas Heaven



CAN WE UNDERSTAND EVERYTHING?

It took 3.8 billion years, but we got there in the end. For most of the history of life on Earth, life was pretty dull. Then humans evolved, and things got interesting.

One of the defining features of our species is our ability to make connections. From birth, we can't help but recognise patterns. Arrangements of dark and light resolve into faces, sounds into voices. Some of these patterns become more abstract rules about the world – day follows night, things fall down. They allow us to draw inferences about things: a stone falls, therefore an apple will too.

What goes for us individually applies to our species as well. The history of science is the history of seeing ever deeper connections between apparently unrelated phenomena. Newton recognised that the same force that causes an apple to fall also keeps the moon in orbit: gravity. Faraday and Maxwell showed that electricity and magnetism were two sides of the same coin; electromagnetism itself was later united with the weak nuclear force, responsible for things like beta decay.

Each of these unifications reduces the number of separate physical theories required to understand the universe, leading many to believe that it may eventually be possible to unify all of them into a single theory – a much-vaunted theory of everything.

Is that a realistic prospect? Could we, a species of ape with a brain evolved for survival on the African savannah, really figure out the whole thing?

"We've understood an enormous amount about how the world works in an extremely short period of time, cosmically speaking," says Sean

Carroll, a cosmologist at the California Institute of Technology in Pasadena. A century ago, we didn't know other galaxies existed, or that the universe is expanding, he says. And that's just the start. In the past 100 years we have discovered most of quantum mechanics, a whole zoo of new particles, the existence of dark matter and dark energy – and we have woven these and other empirical observations into a series of successful theories about how the universe works. "At this rate, we have every reason to think we can understand it all someday," says Carroll. Or maybe not. Chimps, smart as they are compared with, say, tortoises, will never grasp quantum theory, or even recognise the need for such a theory. And although we are smarter than chimps, why shouldn't there be concepts that are too big or too complex for our brains to handle? In some senses, such unknowables do exist. Turbulent fluids, stock markets, crowd dynamics, even the functioning of our own brains are all impossible

for us to fathom without the help of computer models.

Even if we are capable of understanding everything, there's much work to be done. Our two most successful physical theories – general relativity, which deals with very large things, and quantum mechanics, which deals with very small ones – are maddeningly hard to unify (see "Six principles, six problems, six solutions", page 38).

Similarly, we know of four fundamental physical forces: electromagnetic, weak nuclear, strong nuclear and gravity. Three of these forces play nicely with each other in the form of the standard model, our best description of how fundamental particles interact. The odd one out? Gravity.

Unifying gravity and the standard model would be a huge step towards a theory of everything. Our best shot so far is string theory, which recasts all phenomena as the result of tiny vibrating strings interacting with each other. The problem is, we don't have a good way to test it. And without

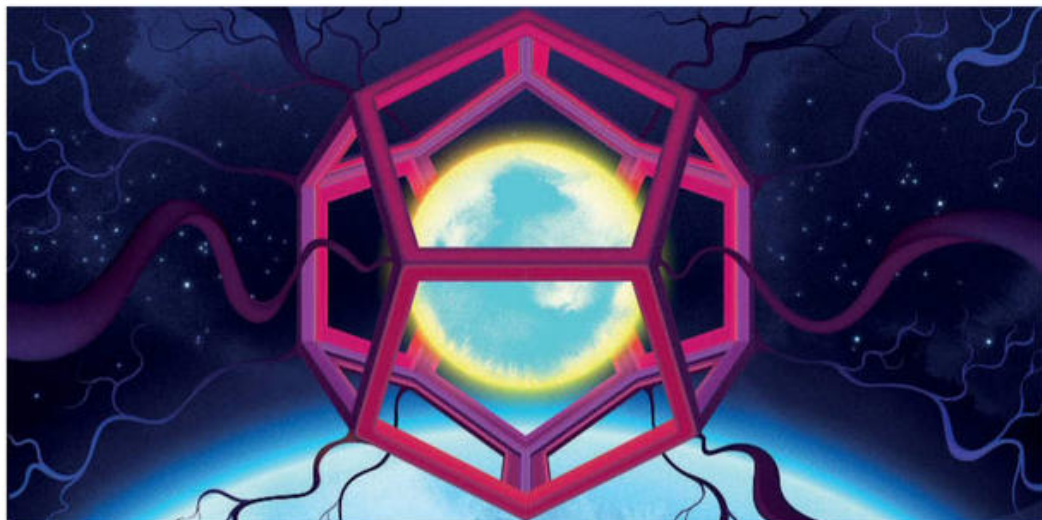
verification by experiment, how can we say we really "understand" it?

Nonetheless, there's no reason to think we won't eventually be able to test our theories and understand the cosmos, says Peter Woit, a mathematician at Columbia University in New York.

So what happens when we do fully understand the cosmos? If knowledge is power, how powerful will it make us? Woit says there's an outside possibility that some insight will lead to a *Star Trek* future of warp drives and wormholes. But it could just as easily show why these things are impossible.

A theory of everything could also have profound cultural impacts, perhaps telling us that we are, after all, the centre of the universe (see page 86), or a holographic projection from the edge of it. What is sure is that we will keep on striving. "The point of searching for a theory of everything isn't to do things," says Carroll. "It's to understand how the world works. Discovery is its own reward."

MacGregor Campbell



4

COULD WE DESTROY THE UNIVERSE?

With great power comes great responsibility. As our grip on Earth grows ever tighter, so does the possibility that we could destroy it, or at least ourselves. But the prospect pales into insignificance when you consider that we may have the power to do something even worse.

We could destroy the universe.

Remember the outcry when CERN was getting ready to start smashing particles together in its Large Hadron Collider (LHC)? A few doomsayers warned that it might be opening the door to the apocalypse.

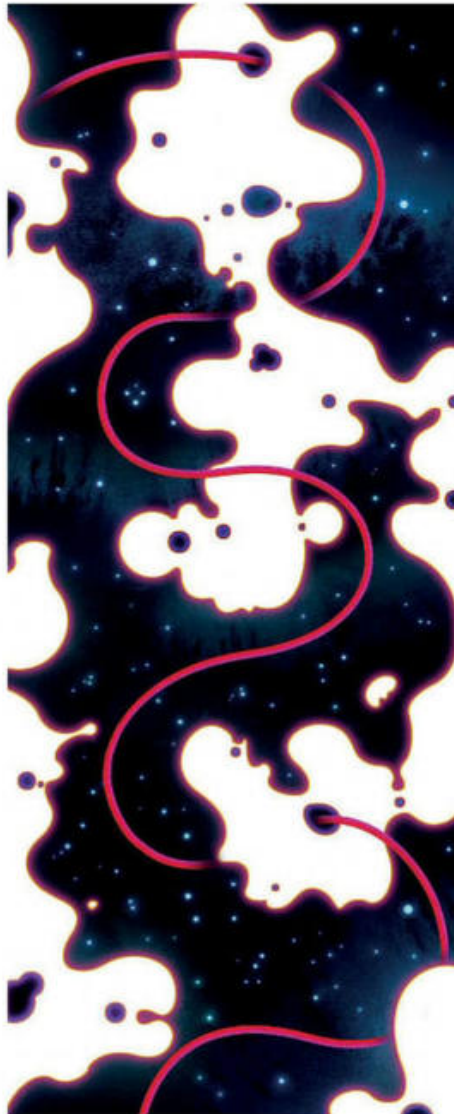
This existential angst was triggered by the prospect of protons colliding at extremely high energies. Einstein's general theory of relativity suggests that concentrating this kind of energy in a volume smaller than an atom might distort space and time enough to tear a hole in the fabric of the universe. This "mini black hole" could rapidly expand to engulf the entire cosmos.

CERN took the possibility seriously enough to carry out the ultimate workplace health and safety assessment. In 2008, it declared the disaster scenario virtually impossible. That assessment still stands, even though the LHC has now powered up to almost double its original energy.

We aren't completely off the hook, however. That's because the Higgs boson, discovered in the LHC in 2012, has given us reason to believe we might destroy the universe in a completely different way.

This danger was first pointed out in 2008 by physicists Lawrence Krauss and James Dent, both then at Case Western Reserve University in Cleveland, Ohio. The problem, they said, is that the universe is governed by the rules of quantum physics, where observations of a system can affect its state (see page 87).

The notion might be familiar to you in the form of Schrödinger's cat. In this thought experiment, a cat is placed in a sealed box with a vial of deadly poison that will be cracked open if a quantum event occurs: the radioactive decay of an atom. According to standard interpretations of quantum theory, as long as the box remains sealed, the cat is



both alive and dead. It is the act of opening the box and observing the state of the cat that determines whether the radioactive decay occurs. In other words, human observation changes the state of the system.

Krauss and Dent suggested that something similar applies to the universe. It is theoretically possible to write down a quantum state for the cosmos. This moves between different states, just like the radioactive atom in the Schrödinger's cat experiment, and can be similarly affected – in theory – by human observations.

An observation of something that is a property of the whole cosmos, such as the dark energy thought to be accelerating the universe's expansion, might cause a sudden shift from being in a mixture of two states to being in one definite state. So looking at a supernova could be enough to alter the overall quantum state of the universe. The result might just "reset" the universe's state, moving it back to where it was a few moments before. But there is a remote possibility of catastrophe.

This is because we are living in what physicists call a false vacuum – essentially an unstable configuration of space and time. That means the universe's quantum state is slowly decaying towards a more stable one. However, an observation could tip it into that state abruptly. The universe would suddenly cease to exist, then reappear as a new, more stable cosmos – without us in it.

Not surprisingly, this was a controversial idea when first raised, not least because we didn't know whether we were living in a false vacuum. However, some of the properties of the Higgs boson tell us that we almost certainly are. "The discovery makes the issues we discussed more relevant," says Krauss, who is now at Arizona State University in Tempe.

We don't know for sure that observing the cosmos can affect its quantum state. If it does, we really could precipitate our universe's demise. But like the LHC black hole scare, it isn't something that should keep us awake at night; Krauss says it was just a thought experiment, not a proof of peril.

Michael Brooks



DOES THE COSMOS KNOW WE'RE HERE?

To the best of our knowledge we are alone in the universe. But if we're not, do the aliens know that they aren't alone? And if they know we exist, how much do they know about us?

It largely depends on who they are and where they live. If they inhabit planets orbiting nearby stars – up to a few dozen light years away – and are of comparable intelligence and technological development to us, they might know we are here, thanks to various messages we have deliberately beamed to an assumed interstellar audience. But that also means their knowledge of us is selective at best, confined to the Beatles, Doritos, theremins and a few other trivialities.

If our neighbours are more advanced – enough to have blanketed their moons in receivers, for instance – they might have been watching the weak TV signals that have beamed from Earth at the speed of light since transmissions really took off after the second world war. Assuming they managed the relatively simple task of decoding the signal, they would know a lot about us: what we look like, how we behave and relate to one another, our breeding habits, culture, history – and predilection for watching trash.

There probably are a few Earth-like exoplanets that are close enough for our broadcasts to have reached them. But the chances of advanced life being on one them at just the right time to listen in is minuscule. And if they are there, they have done a good job of hiding their presence from us.

Beyond such relatively limited distances, the odds of advanced life could be higher, purely on the basis of the numbers. There are several hundred billion stars in our galaxy, a million of them within 1000 light years. But our artificial signals haven't had time to reach them yet. Could civilisations at these distances know

anything about us (see "What if we are not alone?", page 19)?

Technically it is feasible to conceive of telescopes capable of gathering information from vast distances, although it would require a truly astronomical aperture to see anything in detail. One way around this is to use a massive object, like a star or a black hole, as a giant gravitational lens, by seeing how it bends light. If we used our sun this way, which is technically possible although horrendously complicated and expensive, we could make out road networks or detect street lighting on the surfaces of nearby exoplanets, should they exist.

For a much more advanced society, it is conceivable that our ancestors' burgeoning imprint on Earth could have been observed from hundreds or thousands of light years away – although the farther away they are, the less of our history is accessible to them.

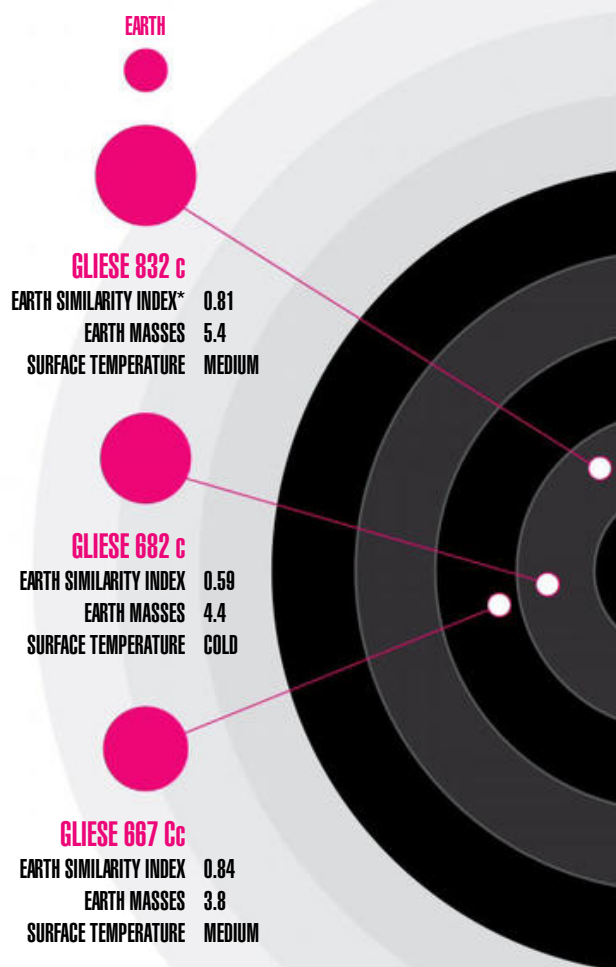
What about societies even more distant? Given our current ability to detect exoplanets, it isn't a huge leap to imagine that civilisations millions of light years from Earth know that our rocky planet is here, in the habitable zone of a yellow dwarf star in an arm of a spiral galaxy. Our planet's 2-billion-year-old oxygen signature may have been picked up along with other spectral hints of ancient life. But the existence of intelligent life would be inaccessible to them.

"If I were an alien society just 100 years more advanced than us, my astronomy textbooks would surely contain huge tables of habitable worlds. Earth would be among them," says Seth Shostak, director of the SETI Institute in California. But they would call Earth something different, perhaps as functional and unglamorous as the names we give to the habitable worlds we know about. Greetings planet KOI-3010.01, we come in peace...

Jon White

HOME FROM HOME

Potentially habitable rocky planets within 50 light years of our solar system



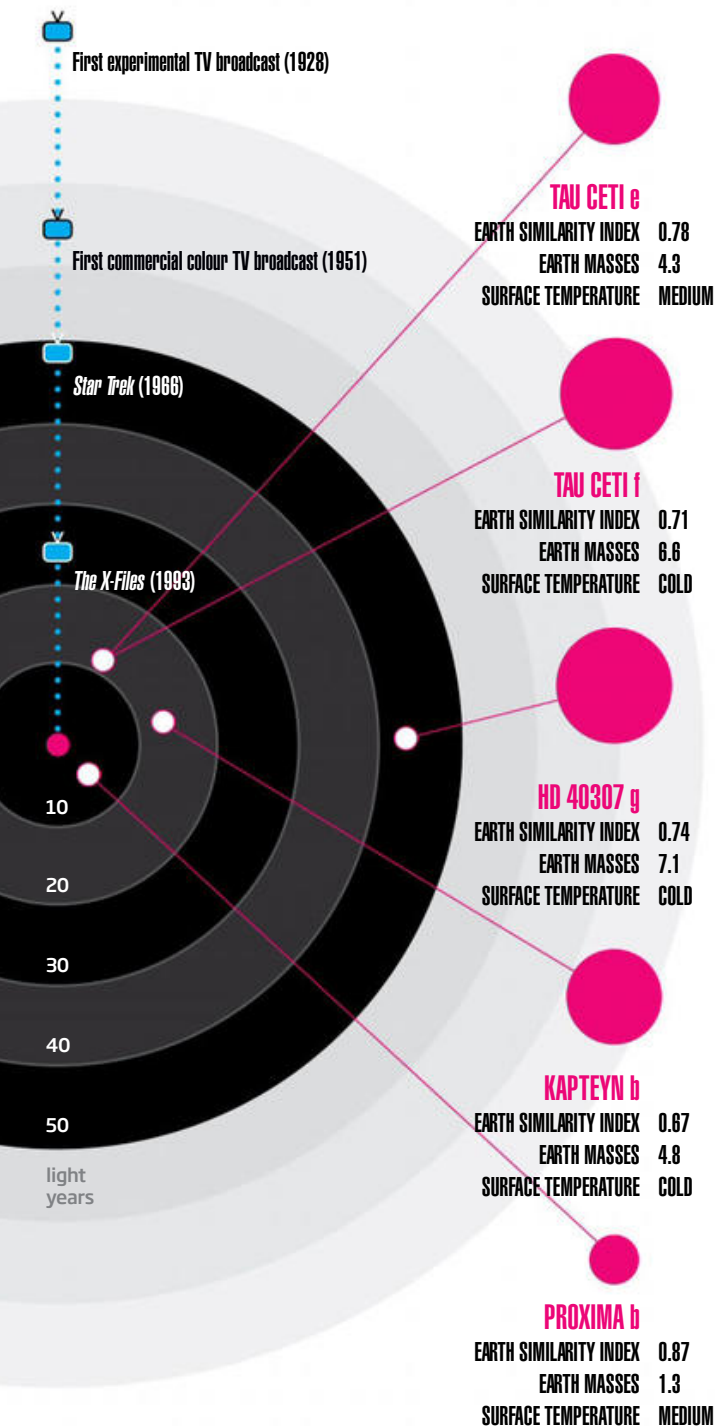
*Earth Similarity Index is a scale from 0 (not similar to Earth) to 1 (exactly like Earth) based on the planet's radius, density, surface temperature and escape velocity. It is not a measure of habitability. Mars has an ESI of 0.64

Earth masses represented by two dimensional surface area

Positions of the dots represent distance from the sun on the plane of Earth's equator. They don't represent distances between exoplanets

BROADCASTING TO THE STARS

TV signals from Earth are travelling outwards at light speed. Even broadcasts from as recently as 1973 have reached and gone beyond these potentially habitable planets.



COULD WE COLONISE THE STARS?

It's fun to speculate about aliens (see left). But what if there are no aliens? It has been 65 years since Enrico Fermi first pointed out our solitude. Fermi estimated that it would take an advanced

technological civilisation 10 million years or so to fill the galaxy with its spawn. Our galaxy is 10,000 times older than that. Where is everybody?

It's not as though we haven't been looking. Not for long, perhaps, and not very hard, but even a crude estimate suggests there should be other advanced civilisations capable of signalling over interstellar distances. And yet - nothing.

So what if we really are alone, or so isolated as to amount to the same thing? "If we think we are the only life in the universe, we have a huge responsibility to spread life to the stars," says Anders Sandberg of the University of Oxford's Future of Humanity Institute. "If we are the only intelligence, we may have an almost equal responsibility to spread that, too." Astrobiologist David Grinspoon, of the Planetary Science Institute in Arizona, agrees, although he hasn't given up on finding ET yet. "We have powers no other species has had before," he says. "If we are it, if we are the best the universe has; if we are the universe's sole repository of intelligence and wisdom and scientific insight and technology, it ups the ante quite a bit. We have a responsibility to preserve our civilisation."

It won't be easy. First, we need to decide where to boldly go. We don't know if humans can survive for any meaningful length of time anywhere except the surface of Earth. "Nowhere in our solar system offers an environment even as clement as the Antarctic or the top of Everest," says the UK's Astronomer Royal Martin Rees. But some pioneers aim to give it a go anyway. Billionaire inventor Elon

Musk is aiming to establish a self-sustaining colony on Mars in the next few decades. "By 2100, groups of pioneers may have established bases entirely independent from Earth," Rees says.

Second, we are going to need some serious propulsion power but we don't yet know what that will look like. Third, we have to have some way to deal with interstellar dust, which could create catastrophic collisions with our craft at the speeds we would need to attain. Fourth, we would need some kind of artificial gravity on board, otherwise the crew will suffer massive, possibly fatal, health issues.

There will undoubtedly be many more obstacles that we have yet to confront or even imagine. But Sandberg and others are optimistic we can overcome them. Even if we can't, we could play the longer game and attempt to seed the galaxy with life via "directed panspermia". The basic idea is to launch microorganisms into space in the hope that they will crash-land on a planet or moon suitable for life, and eventually evolve into a self-aware, intelligent species.

Science fiction author Charlie Stross suggests isolating spore-forming archaea and photosynthetic bacteria that can survive for long periods in the harshest of environments. "Put them on rockets and fire them out of the solar system," he says. "Almost all will perish, but if you launch a hundred tonnes of spores every year for a century, maybe sooner or later something will work."

There would be no real payback for us, except perhaps returning a favour. Life on Earth may have started by directed panspermia (see "What if we came from space?", page 22). If so, our ultimate purpose may be to pass it on again, like a cosmic chain letter.

Michael Brooks

7

CAN WE ENGINEER THE UNIVERSE?

Humans have begun to transform the Earth. We have built cities, transport networks and power stations, and sprinkled the skies with satellites. If we extrapolate this ability to engineer our own environment – for living space, travel, energy and communications – where does it lead us? Could we transform space too?

Predicting the far future is a fool's game.

So let's take the usual dodge and say: unless something is forbidden by known physics, it will be done. Eventually.

Before we start, let's invent two things: self-repairing AI supervisors that can direct projects lasting many millennia; and vehicles that can reach close to the speed of light, maybe riding on laser beams or driven by miniature black holes – which according to recent calculations by physicists at Kansas State University may be possible.

Thus tooled up, we could hop from solar system to solar system, sweeping across the galaxy in 10 million years or so, and then out into our local supercluster of galaxies. So the potential building site is quite spacious.

Such a civilisation would consume lots of energy, and that is where our engineering may be most conspicuous. One option will be to plug into local power sources, such as harnessing starlight with orbiting solar power stations. As demand for power grows, lots of these could be arranged to obscure a star completely, forming a closed "Dyson sphere", named after physicist Freeman Dyson, who pointed out that technological civilisations tend to use ever-escalating quantities of energy.

If we built one we would darken the sun and leave a vast archaeological ruin in the event of our demise. Today, Earthly astronomers are looking for the darkness cast by alien engineering on this scale.

With this level of technology we could even move stars around, albeit slowly. The simplest way would be to place a mirror on one side of the star to reflect some of its light into a beam, producing thrust in the opposite direction. Or the energy from a Dyson sphere could power ion engines to move the star a bit faster. We might use such a stellar engine to coast away

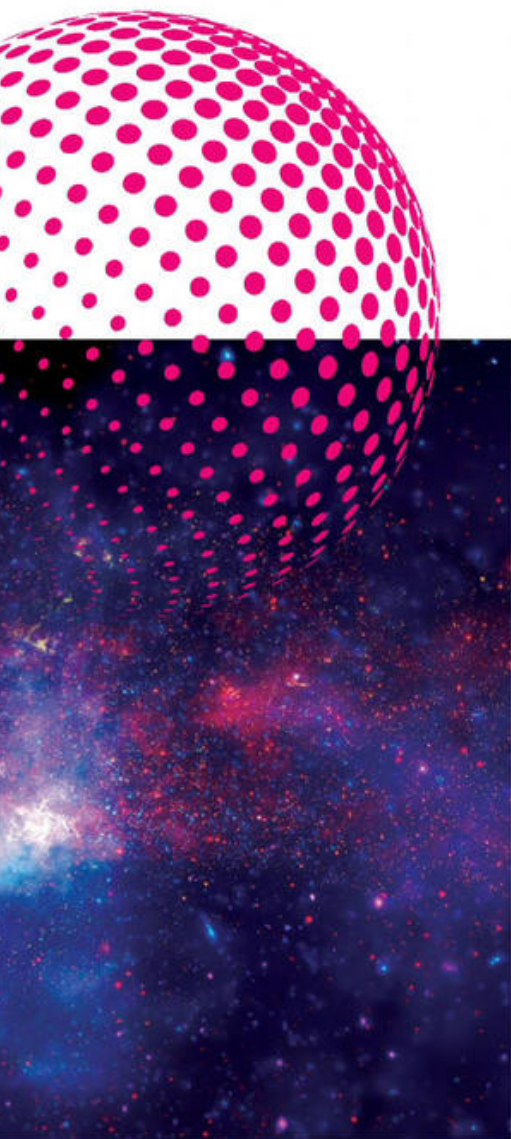


from a predicted supernova, or to take two small dim stars and smash them together to make a brighter power plant.

If wrangling mere stars seems humdrum, how about harnessing the power of a supermassive black hole? We could catch the radiation from its accretion disk, or suck energy out of its spin. A spinning hole drags space-time around it in a region known as the ergosphere, which we could exploit in at least two ways. Roger Penrose at the University of Oxford has suggested using it to accelerate a stream of matter to high speeds, whereas Roger Blandford of Stanford University and Roman Znajek, formerly at the University of Cambridge, devised a way to turn it into an electromagnetic dynamo. These could be the basis of a power plant a billion times as powerful as a Dyson sphere. It would have to be the size of our solar system, at least.

Even that might not be the limit of our ambition. Our quest to understand the cosmos (see "Can we understand everything", page 88) may lead us to build the ultimate particle accelerator, capable of reaching the immense energy where all forces are unified and the fundamental nature of space-time is finally revealed. Brian Lacki at the Institute for Advanced Study in Princeton, New Jersey, has worked out some of the properties of this machine. One of them is immense size: to be able to boost particles to the required energies, it would have to stretch at least a hundred times the distance from the sun to Pluto.

This is just a lower limit, but making it even bigger should be possible. Such a long, thin object can be extended indefinitely without producing overwhelming gravitational stress, so we might be able to build a tower out to Orion and beyond.



NASA/ESA/SSC/CXC/STSC

At the limits of imaginable technology, we might even end up tinkering with the fate of the cosmos. If our hunger for power isn't satisfied by stars and supermassive black holes, then we might learn to create microscopic black holes and feed them with dust. This could unlock the mass-energy of inert matter, turning it into Hawking radiation (see page 125) that could drive our interstellar industry.

According to calculations made by S. Jay Olson while at the University of Queensland in Australia, this could change the future of everything. With civilisation spreading through space at close to the speed of light, it would fill the cosmos with waste heat and so change its physical properties. The conversion of matter to radiation would even slow down the expansion of space a little, which puts our petty meddling with Earth into perspective. **Stephen Battersby**



COULD WE BECOME GODS?

We are a curious species, and our curiosity has led to some interesting ideas about our place in the universe: gods, evolution, quantum consciousness and the multiverse.

But perhaps the most curious of all is the idea that the universe isn't real, and that we live in a computer simulation created by a superior intelligence. In fact, according to Nick Bostrom, the University of Oxford philosopher who developed the notion, this is the most likely explanation for our existence.

Whatever the plausibility of this claim, it begs a tantalising question: could we ever create such a simulation? Could we become the gods of an artificial universe inhabited by creatures so smart they are able to question their own place in their universe?

The first requirement would be to create artificial intelligence that can carry out the same range of intellectual tasks as a human. According to cognitive roboticist Murray Shanahan of Imperial College London, there's no reason to think we can't, although it could take decades. "There's nothing magical about the brain; it doesn't transcend physics. So of course it is possible to build a physical entity that can do anything we can do," he says.

But it will take more than brute computing power to build a brain. "What matters is structure, the pattern, the connections," says Peter Bentley at University College London, and we don't yet have a detailed enough blueprint of the brain to reproduce that. But the European Union's 10-year Human Brain Project is working on it.

In the meantime, simpler brains are already being simulated. A project called OpenWorm is putting the finishing touches to a virtual version of the tiny nematode worm *Caenorhabditis elegans*, including its rudimentary nervous system of 302 neurons. This relative simplicity has allowed the connections between all its cells and its entire repertoire of behaviours to be mapped and simulated.

Is this taking us towards truly intelligent, life-like brain simulation? "It could be a first step in that direction," says Stephen Larson, who runs the OpenWorm collaboration from San Diego, California.

But a virtual brain by itself isn't going to learn anything, let alone question its place in its world. It needs a range of senses and an environment with which to interact. Current technology has a long way to go. "We need a supercomputer just to compute the electron cloud around one atom. And there's quite a lot of atoms in our world," says Bentley. Fortunately, the goal isn't to recreate everything we know about the universe, but something rich enough for simulated beings to get their digital teeth into. We may also decide to bury some fossils in the simulated earth, to throw our creations off our scent.

If and when we get there, how should we treat such creations? What kind of gods would we be? Capricious ones, perhaps: there are web pages devoted to sadistic ways to kill characters in *The Sims* video games.

But Old Testament-style wrath could give way to a gentler approach if we appreciated what we have created. "We've got to get away from the idea that computer software equals unreal," says Bentley. "Software is a bunch of electrons - a type of lepton - whizzing about in specific patterns within the electronics of your computer. And what are you? A bunch of quarks and leptons whizzing about in specific patterns."

Bostrom agrees. "I think we should try to treat all sentient creatures compassionately, whether they are digital or not," he says.

Before you get dizzy with the prospect of omnipotence, bear in mind where we started: there's a better-than-evens chance that you and everything you know is already part of a simulation. That wouldn't stop us creating a simulation within our simulation, and so on ad infinitum. But it puts a different perspective on our place in the grand scheme of things.

Sean O'Neill

The now delusion

Do past, present and future exist only inside our heads? **Michael Slezak** investigates





IMAGINE standing outside the universe. Not just outside space, but outside time too. From this spectacular vantage point, you gaze down upon the universe. At one end you see its beginning: the big bang. At the other, you see... whatever it is that happens there. Somewhere in the middle is you, a minuscule worm: at one end a baby, the other end a corpse. From this impossible perspective, time does not flow, and there is no “now”. Time is static. Immutable. Frozen.

Fantastical as it seems, for most physicists today the universe is just like that. We might think of time flowing from a real past into a not-yet-real future, but our current theories of space and time teach us that past, present and future are all equally real – and fundamentally indistinguishable. Any sense that our “now” is somehow special, or that time flows past it, is an illusion we create in our heads.

Physics, in fact, has killed time as we know it. The question is: do we need it back?

It was Newton who began to stick the knife into now. His laws of motion, formulated late in the 17th century, were the first to capture time in mathematical equations. Soon it was natural to depict motion on a graph with time on a spatial axis. Once that was done, any special, unique point of “now” started to look as subjective as a “here” on a map of space.

Einstein landed the fatal blow at the turn of the 20th century. According to his special

theory of relativity, there is no way to specify events that everyone can agree happen simultaneously. Two events that are both “now” to you will happen at different times for anyone moving at another speed. Other people will see a different now that might contain elements of yours – but equally might not. “You can define it, but people won’t necessarily agree,” says physicist Sean Carroll of the California Institute of Technology in Pasadena.

The result is a picture known as the block universe: the universe seen from that impossible vantage point outside space and time. You can by all means mark what you think is “now” with a red dot, but there is nothing that distinguishes that place from any other, except that you are there. Past and future are no more physically distinguished than left and right. There are things that are closer to you in time, and things that are further away, just as there are things that are near or far away in space. But the idea that time flows past you is just as absurd as the suggestion that space does.

Contradicting reality

George Ellis, a cosmologist at the University of Cape Town, South Africa, does not buy any of that. The block universe contradicts every single experience we have, he says. “It doesn’t represent the passage of time, and that’s one of the most fundamental features of daily life. So it’s a bad model of reality.” What’s more, accept it and any attempt to understand anything about anything becomes meaningless. “The whole process of doing science depends on time rolling on. We make a hypothesis, test it, accept it or reject it – the process rolls on in time.”

Back in 2006, Ellis began to sketch a different picture. His starting point was not relativity, but quantum physics. A strange fact about quantum physics is that indeterminate future outcomes are seemingly governed by probabilities in the present. Quantum objects exist in “superpositions” of more than one state until such time as we measure them, when they adopt one or other of their possible forms. The most notorious illustration is Schrödinger’s cat: locked in a box with a vial of poison whose seal may or may not be intact, ➤

“Our current theories of space and time teach us that past, present and future are all equally real – and fundamentally indistinguishable”

"We live on an edge of the universe, on a surface we call the present that shimmers into existence one moment at a time"



it is simultaneously dead and alive – until you open the box, when it is most definitely one or the other.

Such quantum oddities are a blow to the block-universe conception of an equally real past, present and future, says Ellis. “Even if you know everything about the state of the universe today, you can’t predict what will be tomorrow. The future can’t be real because it’s not even fixed yet.”

For Ellis, quantum physics supplies an objectively defined present moment: it is the boundary between what our experiments have determined and what remains to be determined. We live on the leading edge of a “growing block” universe, on a surface we call the present that shimmers into existence one

moment at a time as quantum measurements are made.

Ellis thinks it is perfectly possible to define this “now” within relativity, too. Einstein’s general theory of relativity, published a decade after his special theory, is a full picture of space and time, describing how a combined space-time is warped by the presence of matter to produce the force we call gravity. If we gathered enough data and had a big enough computer, we might take account of all the space-time distortions of all the galaxies, black holes and other matter in the universe to calculate a 3D surface on which each point is exactly the same age as the point where we are. “Space-time is defined up to then and not beyond,” says Ellis.

This present is still not “now” as we know it, because not everything on this 3D surface happens simultaneously: as demanded by special relativity, if you and I are moving at different speeds on it, we will still disagree on what is happening now. But that doesn’t necessarily matter. Within relativity, things that are causally related to one another happen in the same order from all perspectives, even if individual observers can’t agree on exactly when they happened. “That’s just psychology,” says Ellis. “It makes you feel happy to think this is simultaneous with that, but it doesn’t mean anything for physics.”

There are still wrinkles in the growing block. Quantum theory reveals that the future is indeterminate, and that aspects of the present

are, too: Schrödinger's poor feline is an example, if we don't bother to check whether it is alive or dead. Ellis's solution, formulated with his colleague Tony Rothman in 2009, is that the present is not a solid surface, but one pitted with indeterminacies that gradually solidify into certainties. These gaps in the present are not something we'd notice: the cat notwithstanding, quantum indeterminacies can only occur for very small things, and over small timescales. "The holes in the present aren't going to be big enough to fall through," says Ellis.

He is still working to fill in gaps in the theory, most recently how the creation of the future cascades down from the cosmological to the quantum scale.

Not everyone is convinced he is on the right track. Huw Price, a philosopher of physics at the University of Cambridge, isn't persuaded by the premise of the present as a dividing line between a real past and an unreal future. Even if the future is indeterminate, he says, it still can be real: you might not be able to determine what's on the other side of a mountain from your current location, but that doesn't mean it doesn't exist.

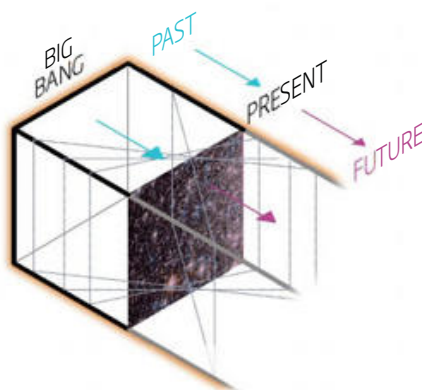
Carroll's beef is that Ellis's argument depends on the truth of the "Copenhagen" interpretation of quantum mechanics. This is the idea that acts of measurement determine the world's future trajectory, and it is the most popular way among physicists to square quantum theory's indeterminacy with the decidedly determined world around us. Carroll prefers the "many worlds" scenario, in which every quantum possibility occurs in different universes: the present Schrödinger's cat is dead in some universes, but alive in others. The cat's future is just as defined as its past; it just has many possible futures. If this interpretation – or any other of the many interpretations of quantum theory – is correct, Ellis's way of defining the present vanishes.

That's one reason why theoretical physicist Lee Smolin of the Perimeter Institute in Waterloo, Ontario, Canada, thinks that we must be more radical to rescue time. In his recent book *Time Reborn*, he argues that if we want to square how we perceive time with what physics tells us about it, it's no good adapting the block universe: we must throw it out altogether.

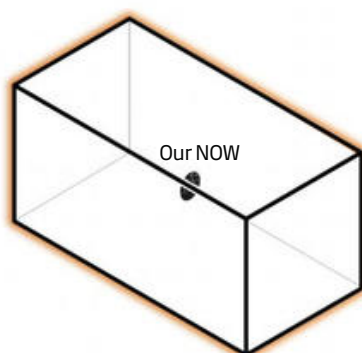
Smolin's starting point is a reformulation of general relativity known as shape dynamics, developed by the independent physicist Julian Barbour and others. Whereas in relativity space and time stretch and condense for observers travelling at different speeds,

About time

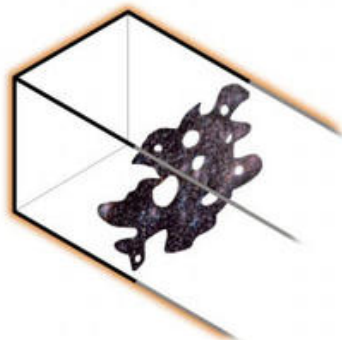
We perceive time as flowing past us from a real past to an as-yet undetermined future. But what's the reality?



Einstein's relativity tells us that time does not flow past a uniquely defined present. Observers elsewhere in the cosmos, or moving at different speeds, will all construct very different nows



There is no possible objective definition of now – all points in space and time form a static "block universe"



In the "growing block" universe, relativity is used to calculate the surface of the universe where everything is the same age. Quantum measurements on this surface continually create the present, one that moves forward in time

in shape dynamics only sizes change. Two distant observers will always agree on what's happening "now" in a galaxy regardless of their relative motions; they just won't be able to agree how big things in that galaxy are.

That might seem like a zero-sum game, replacing one uncomfortable principle with another. For Smolin, though, bending only space, rather than space and time, neatly recreates a conception of time of the sort quantum physics uses, one in which a single external clock provides a beat that distinguishes one moment from the next. The great prize on offer is the possibility of unifying our understanding of quantum theory with that of gravity, the only one of the fundamental forces of nature to have no quantum description. The route to a "theory of everything", Smolin thinks, is through a better understanding of time.

A unique present

Once simultaneity is regained, it becomes possible to describe the entire universe as a series of layered moments – a succession of objectively identified times in which all events are simultaneous. "All that exists is this moment," says Smolin. This is unlike the block universe, where past, present and future are equally real, or Ellis's conception, where only the past and the present are. Instead, the only things that are real about the past or future in Smolin's world are signs of them in the present: records of the past and indicators of what is to come in the future. Smolin is working with Marina Cortes from the University of Edinburgh, UK, to flesh out the idea with mathematics, and to explore which of the many theoretical approaches to quantum gravity it is compatible with.

Price is unmoved. Even if Smolin's or Ellis's approach can provide an objective way of defining the present, he says, there is still a big logical hole. On the one hand, such arguments demand that the present moment be unique; on the other, they demand that every other moment also acquire that unique property. "The whole idea of a privileged present moment is incoherent," he says.

Tim Maudlin, a philosopher and mathematician at New York University, has a different objection. Even if Ellis's or Smolin's theory provides a physical basis for our intuitive conception of here and now, neither explains the fact that we see time flowing, whereas physics suggests it is stationary. This is a fundamental omission, says Maudlin. "The notion that time passes is absolutely ➤

commonplace; it is not a bit of technical jargon invented by philosophers.” Without flowing time, he says, nothing would move at all. Things like rivers appear to flow in space, but “it’s the fundamental direction in time that underlies all of these other directionalities”.

For the past few years, Maudlin has been working on what he calls the theory of linear structures, which he hopes will allow him to reincorporate a flowing time into physics. The idea is rooted in mathematics rather than physics: unlike shape dynamics, it doesn’t provide a rival physical basis for the warped space-time geometry introduced by relativity. “It is the language in which to write a physical theory, not a physical theory itself,” says Maudlin, who has published the idea in book-length detail.

The principal addition to this language’s vocabulary is an object called a directed line. In any conventional geometry, lines between two points in space and time do not come with a natural direction: we have to define a line in terms of a coordinate system, specifying that it passes from me to you rather than you to me, or drawing an arrowhead on the line to make things clear. In Maudlin’s geometrical language, however, that arrowhead is implicit in the definition of any line. Once this is built into the fundamental language of geometry, time can naturally acquire a direction.

Ellis thinks Maudlin’s work is interesting, and also compatible with his growing block

“People who believe in physics know that the distinction between past, present and future is only a stubborn illusion”

picture, explaining in more detail how the flow of time can be fundamental to physics. “In the end, you have to base your theories on some fundamental givens. Time, it’s just kind of a given, which everything else flows around,” he says.

Carroll is more sceptical. Rather than attempting to change the block universe to explain our experience of time flowing, he says we should concentrate on explaining human experience in light of what our very successful physics tells us about the block universe. That task, he says, is quite achievable. “That doesn’t mean that we’ve done it yet, but I see no obstacle to doing it.”

Going with the flow

Craig Callender, a philosopher from the University of California, San Diego, agrees. Explaining our apparently aberrant perception of time does not mean we have to overturn physics or invent a whole new way of doing geometry. When, he says, we “embed critters like us” in a universe like ours, it makes sense that we should see a flowing time and

distinguish past, present and future – even when the reality is something different.

To explain why, we can return to that vantage point gazing down on the entire block universe, and zoom in on that tiny human speck: the four-dimensional worm with a baby at one end and a corpse at the other. This worm’s perception of time differs from “reality” first in that it remembers the past but does not see the future. That can be explained as a result of thermodynamics. The universe started off in a highly ordered, taut state after the big bang, and has been expanding into an ever more disordered, flaccid state ever since. There is an infinitude of paths in which the universe can evolve forward in time, but only one path back into its history. Why the universe works like that is another, fundamentally unanswered question – but it means that, purely statistically, we are only ever likely to have a clear view backwards in time.

Even then, you would expect us worms to feel as if we are stationary in time with a view in only one direction, rather what we experience: moving backwards into the future with no clear view of where we are heading. For Callender, the key to this illusion is an important psychological fact about ourselves: we have a sense of identity. According to physics, your life is described by a series of slices of your worm – you as a baby, you as you ate breakfast this morning, you as you started reading this sentence and so on, with each slice existing motionless in its respective time. We generate time’s flow by thinking that the same self that ate breakfast this morning also started reading this sentence. “Really there’s all these different mes at all these different times,” says Callender. “But because I think that I’m identical over time, that’s why time seems to flow, even though it doesn’t.”

So do we really need to mourn time’s passing? Einstein, for one, drew solace from the view of the timeless universe he had helped to create, consoling the family of a recently deceased friend: “Now he has departed from this strange world a little ahead of me. That means nothing. People like us, who believe in physics, know that the distinction between past, present and future is only a stubbornly persistent illusion.” So it goes. ■



Is time in need of repair, or can the universe cope without it?



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Hooper.

world.

I'M NONE of these. Not in this universe. But in the multiverse I'm all of them, and more.

I'm not a megalomaniac or a fantasist, but I do have a fascination with what-ifs. In the many worlds interpretation of quantum mechanics, every decision I take in this world creates new universes: one for each and every choice I could possibly make. There's a boundless collection of parallel worlds, full of innumerable near-copies of me (and you). The multiverse: an endless succession of what-ifs.

In one of those worlds, I've just written a paragraph which explains that more clearly.

This worries me. If many worlds is correct – and many physicists think it is – my actions shape the course not just of my life, but of the lives of my duplicates in other worlds.

"In the many worlds interpretation, when you make a choice the other choices also happen," says David Deutsch, a quantum physicist at the University of Oxford. "If there is a small chance of an adverse consequence, say someone being killed, it seems on the face

of it that we have to take into account the fact that in reality someone will be killed, if only in another universe."

Should I feel bad about the parallel Rowans that end up suffering as a result of my actions? If I drive carelessly here, I might get a fine, but one of my other selves might crash and kill himself. Or worse, kill my parallel family. How am I supposed to live with the knowledge that I am just one of umpteen Rowans in the multiverse, and that my decisions reach farther than I can ever know?

You might think I should just ignore it. After all, the many worlds interpretation says I'll never meet those other versions of me. So why worry about them?

Well, most of us try to live by a moral code because we believe the things we do affect other people, even ones we'll never meet. We worry about how our shopping habits affect workers in distant countries; about as-yet-unborn generations suffering for our carbon emissions. Deutsch points out that we readily ➤

LUCAS SIMÕES

accept that attempted murder has moral implications, albeit less serious than actual murder. So why shouldn't we afford some consideration to our other selves?

Max Tegmark, professor of physics at the Massachusetts Institute of Technology, understands my quandary. A leading advocate of the multiverse, he's thought long and hard about what it means to live in one. "I feel a strong kinship with parallel Maxes, even though I never get to meet them. They share

and more physicists over the past 50 years. "Multi-universe physics has the same kind of experimental basis as the theory that there were once dinosaurs," says Deutsch.

Nor can we avoid its consequences. Every time we make a decision that involves probability – such as whether to take an umbrella in case of rain – our decision causes the universe to branch, explains Andreas Albrecht at the University of California, Davis. In one universe, we take the umbrella and stay

of humanity," he says. "No, it was somehow tidier to have the universe *be* the cosmos. But actually now I'm liking it more, now that you've pointed out that it's really like the ultimate step in the marginalisation of human beings. I think that's much better. I enjoy that."

Enjoyable though the multiverse might be as a concept, it's tough for us humans to get our heads around its implications – even for physicists themselves. When Tegmark's wife was in labour with Philip, their eldest son, he found himself hoping that everything would go well. Then he admonished himself.

"It was going to go well, and it was going to end in tragedy, in different parallel universes. So what did it mean for me to hope that it was going to go well?" He couldn't even hope that the fraction of parallel universes where the birth went well was a large one, because that

Multi-universe physics has the same kind of experimental basis as dinosaurs



my values, my feelings, my memories – they're closer to me than brothers," he says.

Taking the cosmic perspective makes it difficult for Tegmark to feel sorry for himself: there's always another Max who has it worse than him. If he has a near-miss while driving, he says he takes the experience more seriously than he did before he knew about the multiverse. "The minimum tribute I can pay to that dead Max is to really think through what happened and learn some lessons."

Tegmark is obviously a multiverse believer (see "50 ways to test the multiverse", page 34). Once, he would have been an outsider. When many worlds was first proposed by Hugh Everett, then a graduate student at Princeton University, it met with a scornful reception. Everett struggled to get it published, and eventually left academia in disgust. But its elegant explanations for some puzzling quantum phenomena have convinced more

dry; in another, we don't, and we get wet. The fundamental variability of the universe forces such choices upon us. "There's no escaping them," says Albrecht.

That's a momentous realisation. We're living in a time akin to Copernicus realising that Earth wasn't at the centre of the universe, or when Darwin realised that humans were not created separately from the other animals. Both of those realisations reshaped our conception of our place in the universe, our philosophy and morality. The multiverse looks like the next great humbler of humanity.

"That these worlds are actually out there somewhere, but we cannot access them: I think that's a remarkable thing," says physicist Seth Lloyd, a colleague of Tegmark's at MIT. "It's sort of distressing really." Why, I ask: because it diminishes humanity's status even more? "No, not for that reason. I've always enjoyed the gradual marginalisation

fraction could in principle be calculated. "So it doesn't make any sense to say 'I'm hoping something about this number'. It is what it is."

Hope, it turns out, is the next casualty of the multiverse. You make a decision, and you end up on a branch of the multiverse with a "good" outcome, or you find yourself on a "bad" branch. You can't wish your way on to a good one. Tegmark acknowledges this is not easy to live with. "It's tough to get your emotions to sync with what you believe," he says.

Too tough for me. How am I meant to live without hope?

Slippery concept

What do other non-specialists make of the multiverse? When Hugh Everett died in 1982, aged just 51, his teenage son Mark found his body. I asked him if his father's work had influenced him. "Although I consider

FOUR ASPECTS OF THE MULTIVERSE

THE WAVE FUNCTION

This mathematical entity describes the properties of any quantum system. Such properties - an atom's direction of spin, say - can take several values at once, in what is known as quantum superposition. But when we measure such a property we only get a single value - in the case of spin, it is either up or down.

In the traditional Copenhagen interpretation of quantum mechanics, the wave function is said to "collapse" when the measurement is taken, but it isn't clear how this happens. (Schrödinger's famous cat, neither alive nor dead until someone looks inside its box, illustrates this.) In the multiverse, the wave function never collapses: rather, it describes the property across multiple universes. In this universe, the atom's spin is up; in another universe, it's down.

► myself an Everettian by default, it's all beyond me for the most part, having inherited none of my father's mathematical smarts," says Mark, long-time frontman of the band Eels. "How can I grasp any of it except in small moments? I'm having a hard enough time dealing with this world lately. I only hope some of the other worlds are easier for me to figure out."

I know how he feels. Perhaps a philosopher can help me take a broader perspective. I turn to David Papineau of King's College London. "Say you put your money on a horse that you think is a very good bet," he says. "It turns out that it doesn't win, and you lose all your money. You think, 'I wish I hadn't done that.' But you brought benefits to your cousins in other universes where the horse won. You've just drawn the short straw in finding yourself in the universe where it lost. You didn't do



WAVE-PARTICLE DUALITY

In the landmark experiment, photons are sent one at a time towards a pair of slits, with a phosphorescent screen behind them. Take a measurement at either slit, and you'll register individual photons passing particle-like through one or the other. But leave the apparatus alone, and an interference pattern will build up on the screen, as if each photon had passed through both slits simultaneously and diffracted at each, like a classical wave (see "Where does quantum weirdness end?", page 49). This has been called the "central mystery" of quantum mechanics. In the Copenhagen interpretation, it is down to wave function collapse. Left to its own devices, each photon would pass through both slits simultaneously: the measurement at the slit forces it to "choose". One way to explain the interference pattern through many worlds, by contrast, is that each photon only ever goes through one slit - the pattern comes about when a photon interacts with its clone passing through the other slit in a parallel universe.

anything wrong. There's no sense that the action you took earlier was a mistake."

Hmm. I doubt "I didn't make a mistake" would get much traction with my partner if I bet all our savings on a horse this afternoon and find myself on the "wrong" branch. But then, that wouldn't be the sensible thing to do - and one of the great attractions of Everett's interpretation, according to Papineau, is that it's not "messy", as long as you act rationally.

With orthodox thinking, there are two ways of evaluating risky actions, he explains. First, did you make the choice that was most in line with the odds? If we needed money, and my stake had been proportionate, it might have been. Second, did it work out well? There are any number of reasons it might not - the horse might fall, or just defy the odds and trail in last. ►

It offends Papineau that these two ways of being “right” – choosing wisely and getting lucky – don’t go hand in hand. “The idea that the right thing to do might turn out to have been the wrong thing seems to me to be a very ugly feature of orthodox thinking,” he says. This doesn’t arise in the many-worlds interpretation, where every choice is made and every outcome occurs. That leaves no place for hope or luck, but nor does it leave room for remorse. It’s an elegant, if cold-blooded, way to look at things.

This elegance has always been part of the multiverse’s appeal. In quantum mechanics, every object in the universe is described by a mathematical entity called a wave function, which describes how the properties of subatomic particles can take several values

split every time a measurement is made – or in human terms, whenever we make a decision with multiple possible outcomes. That’s the many worlds interpretation.

God of elegance

For Don Page, a theoretical physicist at the University of Alberta in Edmonton, Canada, this elegance goes far beyond human actions. Page is both a hard-core Everettian and a committed Christian. Like many modern physicists, he agrees with Everett’s stance that collapsing the wave function is unnecessarily complicated. What’s more, for Page it has a happy side effect: it explains why his God tolerates the existence of evil.

“God has values,” he says. “He wants us to

will, because he feels we live in a reality in which God determines everything, so it is impossible for humans to act independently. But in the many worlds interpretation every possible action is actually taken. “It doesn’t mean that it’s fixed that I do one particular course of action. In the multiverse, I’m doing all of them,” says Page.

There are limits to Page’s willingness to leave his fate to the multiverse, however. Seth Lloyd once offered him \$1 million to play quantum Russian roulette, which is a good game for a multiverse aficionado: you can’t lose (see below right). Page thought about it, then declined: he didn’t like the thought of his wife’s distress in the worlds where he died.

Like Tegmark, Page seems to value the multiverse for the perspective it offers.



**“God wants us to
enjoy life. But he also
wants to create an
elegant universe”**

simultaneously. The trouble is, this fuzziness vanishes as soon as we measure any of those properties. The original explanation for this – the so-called Copenhagen interpretation – says the wave function collapses to a single value whenever a measurement is made.

Hugh Everett called this enforced separation of the quantum world from the everyday, classical one a “monstrosity”, and decided to find out what happened if the wave function did not collapse. The resulting mathematics showed that the universe would

enjoy life, but he also wants to create an elegant universe.” To God the importance of elegance comes before that of suffering, which, Page infers, is why bad things happen. “God won’t collapse the wave function to cure people of cancer, or prevent earthquakes or whatever, because that would make the universe much more inelegant.”

For Page, that is an intellectually satisfying solution to the problem of evil. And what’s more, many worlds may even take care of free will. Page doesn’t actually believe we have free

“One of my teenage children wants to get a motorcycle, which my wife and I think is pretty dangerous,” Page says. “But if I say: ‘Okay, maybe most of the time you’d survive, but there’s going to be some part of you, some branch, in which you get seriously maimed in a motorcycle accident’... Maybe I’ll try it.”

Double Deutsch

I’m somewhat relieved to find that even many worlds experts ultimately behave in much the same way as people who know nothing of it. But I’ve also realised that it shapes the way they think about their decisions. Perhaps it’s more natural for us to think about how our actions affect our “other selves” than about the arid probabilities of risk and reward.

If anyone’s going to buck this trend, it’s surely Deutsch, probably the most hard-core of Everettians. Surely he can give me the last word on what it means to live in ➤



QUANTUM COMPUTING

Though quantum computers are in their infancy, they are in theory incredibly powerful, capable of solving complex problems far faster than any ordinary computer. In the Copenhagen interpretation, this is because the computer is working with entangled “qubits” which can take many more states than the binary states available to the “bits” used by classical computers. In the multiverse interpretation, it’s because it conducts the necessary calculations in many universes at once.

➤ the multiverse. He does, but it is by no means the answer I was expecting.

“Decision theory in the multiverse tells us that we should value things that happen in more universes more, and things that happen in fewer universes less,” he explains. “And it tells us that the amount by which we should value them more or less is, barring exotic circumstances, exactly such that we should behave as if we were valuing the risks according to probabilities in a classical universe.” So the right thing to do remains the right thing to do.

So has my quest been for nothing? Not at all. For one thing, Deutsch’s approach could be wrong, a possibility he accepts, though he is adamant the multiverse exists. But if he’s right, his conclusion only reinforces what his



QUANTUM RUSSIAN ROULETTE

This amounts to playing the role of Schrödinger’s cat. You’ll need a gun whose firing is controlled by a quantum property, such as an atom’s spin, which has two possible states when measured. If the Copenhagen interpretation is right, you have the familiar 50-50 odds of survival. The more times you “play”, the less likely you are to survive.

If the multiverse is real, on the other hand, there always will be a universe in which “you” are alive, no matter how long you play. What’s more, you might always end up in it, thanks to the exalted status of the “observer” in quantum mechanics. You would just hear a series of clicks as the gun failed to fire every time – and realise you’re immortal. But be warned: even if you can get hold of a quantum gun, physicists have long argued about how this most decisive of experiments would actually work out (see “50 ways to test the multiverse”, page 34).

peers have been telling me: the best way to live in the multiverse is to think carefully about how you live your life in this one.

Thinking of what-ifs as having some kind of reality can help us to do that. Tegmark says many worlds has made him think differently about life. He sometimes fears doing something because it feels too big a deal. But then he realises that in the grander context of the multiverse, it’s not big at all – that gives him a booster shot of determination and he just does it. “The multiverse has definitely made me a happier person,” he says. “It’s given me courage to take chances to be bold in life.”

I hope it will do the same for me. We might not stop feeling hope or remorse, but the multiverse can help put those feelings in perspective. And while the multiverse may not require a change in our morality, it can help us think harder about our choices and actions. The cosmos reaches far further than we ever appreciated. But so, it seems, do we. ■



CHAPTER FIVE

WHEREVER NEXT?

THE DEEP FUTURE

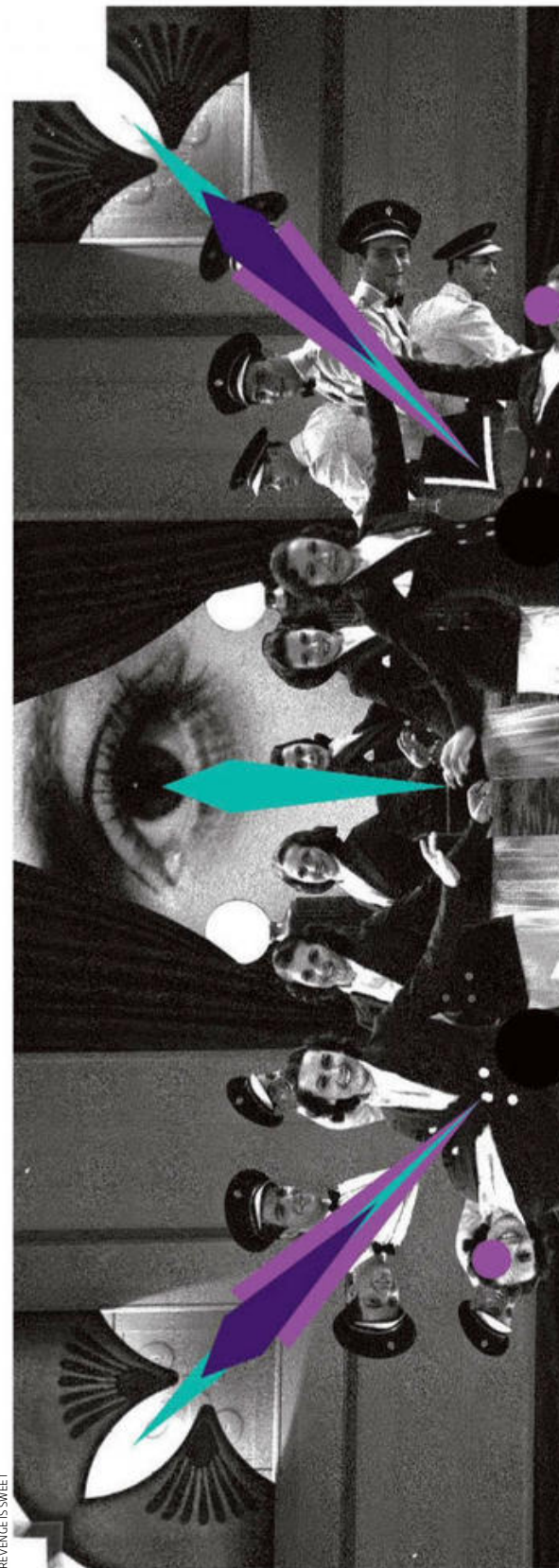
In the 21st century, it can feel as if the future has already arrived. But we're only getting started.

It's fashionable to be pessimistic about our prospects, yet our species may very well endure for at least 100,000 years.

So what's in store for us? We now have the perspective to identify the forces and trends that have shaped humanity and the Earth to date. With this knowledge, we can make intelligent predictions about what is to come. Indeed, many groups are now attempting to extend humanity's horizons far beyond the next century, from the Long Now Foundation to those who say our presence is forging a new geological era.

Over the following pages, *The Collection* tours the coming epoch, from the language we will speak to what our descendants will make of our trash.

The deep future is only just beginning...



REVENUE IS SWEET



10,000 YEARS AGO
FIRST AGRICULTURE

A LIFE IN TIME

100,000 years is an unfathomably long time. Over the next few pages, discover just how many human lifetimes separate you from your descendants in the far future

80-year lifespan

5500 YEARS AGO
FIRST CITIES & CIVILISATIONS

YEAR 0

YOU ARE HERE

YEAR 3000

WHY WE'LL STILL BE HERE

WHAT are the odds we will avoid extinction? In 2008, researchers attending the Global Catastrophic Risk Conference in Oxford, UK, took part in an informal survey of what they thought were the risks to humanity. They gave humans only a 19 per cent chance of surviving until 2100. Yet when you look more closely, such extreme pessimism is unfounded. Not only will we survive to 2100, it's overwhelmingly likely that we'll survive for at least the next 100,000 years.

Take calculations by J. Richard Gott, an astrophysicist at Princeton University. Based on 200,000 years of human existence, he estimates we will likely last anywhere from another 5100 to 7.8 million years.

Fossil evidence is similarly reassuring. Records in the rocks suggest that the average species survival time for mammals is about a million years, though some species survive 10 times as long. It seems there is plenty of time left on our clock. Plus, if you'll excuse the blowing of our own trumpet, we are the cleverest of the mammals.

Mind you, this could be seen as a problem. Probably the greatest threat to an advanced civilisation is technology that runs out of control; nuclear weapons, bioengineering and nanotechnology have all been cited as bogeymen. But disaster expert Jared Diamond, a geographer at the University of California, Los Angeles, points out that we no longer live in isolated civilisations. Humanity is now a global network of civilisations, with unprecedented access to a diverse, hard-won pool of knowledge already being

harnessed for everyone's protection.

We are also unlikely to be extinguished by a killer virus pandemic. The worst pandemics occur when a new strain of flu virus spreads across the globe. In this scenario people have no immunity, leaving large populations exposed. Four such events have occurred in the last 100 years – the worst, the 1918 flu pandemic, killed less than 6 per cent of the world's population. More will come, but disease-led extinctions of an entire species only occur when the population is confined to a small area, such as an island. A severe outbreak will kill many millions but there is no compelling reason to think any future virus mutations will trigger our total demise.

More scary is the prospect of a supervolcano eruption. Every 50,000 years or so, a supervolcano somewhere erupts and ejects more than 1000 cubic kilometres of ash. Such events have been linked with crashes in human population. Around 74,000 years ago, Toba erupted in Sumatra. Anthropologists have suggested that the event may have reduced the human population of Earth to just a few thousand. But as Bill McGuire, former director of the Benfield Hazard Research Centre at University College London, points out, there were far fewer humans then and they were largely confined to the tropics, a geographical concentration that made the eruption's impact much more severe than would be the case with a widely distributed population. "Wiping out 7 billion people today would be far more difficult," he says.

Judging by their historical frequency, it is estimated that the chance of a



ROBERTO CAUDILLO/PLAINPICTURE

"A 400-metre asteroid impact would not be enough to destroy civilisation, but certainly an entire country the size of France"



super-eruption in the next 100,000 years is between 10 and 20 per cent. With colossal clouds of ash plunging the surface of Earth into darkness for five or six years, global harvests would be badly hit for long enough to cause loss of life on an unprecedented scale. "The likely death toll would be in the billions," McGuire says. But it would have to happen twice in that timescale for a realistic chance of human extinction. That's not impossible, just statistically extremely unlikely.

Deep impact

The biggest extinction threats of all come from space. Solar flares, asteroid strikes and bursts of gamma rays from supernova explosions or collapsing stars are what we really need to get through. "Every 300 million years we would expect a gamma-ray burst or a severe supernova explosion that wipes out most of the ozone layer," says Brian

Thomas at Washburn University in Topeka, Kansas, an expert on intergalactic hazards.

The result would be a massive increase in harmful radiation at the Earth's surface and an increased incidence of life-threatening cancers during the decades it would take for the ozone layer to recover. It's impossible to know when such an event might occur.

Yet these things are so rare that the chance of an extinction event in the next 100,000 years is effectively zero. The same can be said for the threat of a solar flare so powerful that it knocks out all critical infrastructure, because it would take flares 1000 times more powerful than the biggest ever seen. "Can our sun, in its present state, produce such a flare very occasionally? We don't know," says Mike Hapgood, a solar physicist based at the Rutherford Appleton Laboratory in Oxford, UK, and project manager for the European Space Agency's Space Weather Programme. But it remains an unlikely disaster scenario. Which leaves the poster child of disaster movies: the asteroid strike.

This one will take some luck to avoid. Space is full of rocky debris that acts as an occasional threat to Earth. It is widely believed that the impact of a 15-kilometre-wide asteroid wiped out the dinosaurs 65 million years ago. In any 100,000-year period we can reasonably expect an impact from a 400-metre asteroid that will cause damage equivalent to 10,000 megatonnes of TNT. "Not enough to do in the whole civilisation, but certainly destroy an entire small country like France," says former astronaut Thomas Jones, who co-chairs NASA's Task Force on Planetary Defence.

Some might argue that without France there is little hope for civilisation anyway, but in reality there is only a 1-in-5 chance of total wipeout. "Global effects come from an impact roughly every 500,000 years, so the odds are about 20 per cent for a catastrophic, civilisation-threatening impact within 100,000 years," Jones says.

We should probably work on some anti-asteroid measures, but really humans concerned about the longevity of our species can relax: the view from here is fine. Michael Brooks

YEAR
5000

WHAT WILL WE BE LIKE?

HERE'S a famous thought experiment about kidnapping a Cro-Magnon man, bathing and shaving him, dressing him in a suit and putting him on the New York subway. Would anybody bat an eyelid?

Probably not. Though Cro-Magnons lived about 30,000 years ago, they were to all intents and purposes modern humans. Physically they were perhaps a little more robust, but behaviourally they were indistinguishable from us, give or take the effects of thousands of years of technological progress on our lives.

We have undoubtedly come a long way since then. A Cro-Magnon in 21st-century New York would recognise almost nothing except for other human beings. But his modern human brain would eventually adjust to the startling new surroundings, much as the Tierra del Fuego native who became known as "Jeremy Button" took to Victorian London after he was brought there in 1830 by Robert FitzRoy, captain of the Beagle.

Now turn that thought experiment on its head and project it into the deep future. What if somebody alive today could be transported to the equivalent of New York 30,000 years - or even 100,000 years - from now? Even if suitably attired, would they fit in?

Impossible to say, of course. Just because we've had more than 1000 generations of biological stasis does not mean we can expect thousands more. If you believe some futurists, we will eventually become cyborgs with prostheses in our brains and nanobots racing around our bloodstream.

Extreme as these technological enhancements may sound, they won't produce changes to our bodies and minds that will be heritable and so alter our fundamental biology. Each generation will have to choose whether or not to become cyborgs, just as people can opt for laser

YEAR
20,000



REVENGE IS SWEET

eye surgery today. For our descendants to be radically different from us, we would have to engineer our own genome or wait for an event that has happened only rarely in our evolutionary line.

One hypothesis to explain the sudden rise in behaviourally modern humans 30,000 to 40,000 years ago is the random appearance of a beneficial genetic mutation, perhaps involved in language. So beneficial was it in fact that the mutation swept through the population. Humans without it would have

been unable to compete with their more fortunate fellows, and their less fit genomes would have been consigned to the scrapheap of evolution.

The “great leap forward” mutation, if it ever existed, will probably never be identified as it has completely replaced the version of the gene that preceded it. But we can see signs of similar sweeps that are not yet complete. For example, a mutation in a gene called *microcephalin* arose around 14,000 years ago and is now carried by 70 per cent of

people. It appears to be involved in brain development, though it is not clear what trait it is being selected for since there is no discernible difference between people who carry it and those who don’t. So it is possible that our descendants could evolve into something similar to *Homo sapiens* today. But radical change seems a long shot.

Of course, we could eventually decide to take evolution into our own hands. In principle, we could engineer ourselves into obsolescence by creating a new breed of human that would outcompete ourselves. The most plausible technology for starting down this road is to genetically engineer sperm or eggs, or early embryos, in order to install changes in their genomes that will be passed down the generations. This is becoming increasingly possible using tools

“It is doubtful that we would genetically engineer ourselves on a scale that would alter the course of human evolution”



such as CRISPR and is likely to be routine in the near future. It has been put forward as a way of stamping out genetic diseases such as cystic fibrosis

Would we go so far as to put desirable traits in rather than just take bad ones out? Even if it were technically possible to do this, it is doubtful that we would collectively agree such changes on a scale that would alter the course of our evolution – unless, of course, engineered humans were so superior that they obliterated the competition.

These possibilities cannot be ruled out. Surely the most likely option is that our time traveller will find himself among friends, a species of human fundamentally the same as us but with cooler technology. Deep down, they will still be human.

Graham Lawton

WHAT WILL WE SPEAK?

SHOULD your descendants uncover this page, yellowed and curling, thousands of years from now, many of these words will be incomprehensible – even if they call themselves speakers of English. After all, we struggle to decipher old English texts like *Beowulf*. You might be able to understand the hero's declaration that “*Béowulf is mín nama*”, but a millennium of language evolution has washed away the meaning from “*grimma gaést Grendel*” – the “ghastly demon Grendel”.

If our language has transformed almost beyond recognition in just 1000 years, how might it sound in tens of thousands of years? Languages are largely shaped by the unpredictable whims of their speakers, but by examining the forces facing our language, we can speculate about how our descendants might speak.

The most obvious question is whether they will be using English at all. Although English is the world's lingua franca, its popularity largely hinges on the present economic importance of Anglophone countries. Should another country come to dominate world trade, our descendants may all be learning its language. If so, it's likely that they would begin to incorporate some of its terms into their own language – in the same way that Italians say that they will listen to a “podcast” on their “tablet” at the “weekend”. But very popular languages tend to be resilient to invasion, so there's no reason to think that English will disappear entirely.

It's more likely that it will splinter and fragment. We can already see new dialects forming in many of the UK's former colonial territories, such as Singapore and Jamaica. Thanks to immigration, the internet and mass media, words from such dialects often feed back through the English-speaking

world – as can be seen in Jamaican variations that are now sweeping through London slang, such as the use of “buff” to mean attractive, and “batty” to mean a person's buttocks. Given enough time, these dialects might diverge entirely. If so, English may end up like Latin – dead, but survived by numerous offspring.

Do such grand transformations make it impossible to predict anything specific about future English? Certainly, the language is changing quickly enough as it is; the *Oxford English Dictionary* adds between 2000 and 2500 words each year, says its senior editor Denny Hilton. But there may be thousands of new words that fail to catch the attention of the *OED*'s lexicographers. When Erez Lieberman Aiden, now at Baylor College of Medicine in Houston, Texas, and Jean-Baptiste Michel at Harvard University studied Google's corpus of digitised books from the last century, they found around 8500 new words entering the language every year. Many of these are rarely used – words like postcoarctation, reptating and subsectoral.

Use it or lose it

By looking at English's journey since *Beowulf*, we can at least identify trends that might continue. Its future grammar might lack some of the nuances that rule the sentences on this page, for instance. We've already lost many of the rules that governed the language of *Beowulf* – English nouns no longer have different genders, for instance.

Today, this ongoing simplification can be seen in the way we use the past tense. There are lots of irregular verbs whose past tenses do not have the more typical “-ed” ending – we say “left” rather than “leaved”, for example. But time is slowly taming these irregular ➤

"English is changing quickly. The *Oxford English Dictionary* adds between 2000 and 2500 words each year"

verbs, and the effect depends on how common these verbs are. By studying English texts from the last 1000 years, Lieberman Aiden and Michel noticed that the less a verb is used, the more likely it is to become regular. "If a word is rare, we don't always remember if it is irregular," says Lieberman Aiden – so we assume it follows the pattern of more familiar verbs.

"To wed", which is now used in only very specific contexts, is already in the throes of change. People are beginning to say they are "newly wedded" rather than "newly wed", for example. Others are more stubborn. Having found the way a word's popularity can influence its chances of linguistic change, Lieberman Aiden and Michel started to predict the future lifespan of certain irregular verbs. For instance, given its relative rarity, there is a 50 per cent chance that "slunk" will become "slinked" within 300 years (see diagram, below).

"To be" or "to have", which are used in around 1 in 10 sentences, have "half-lives" of nearly 40,000 years. The researchers speculate that irregular plurals will follow a similar trend – "men" could become "mans", for example – though they haven't tested the idea yet.

In a similar way, we can predict

which words will be ousted by new coinages or terms imported from another language.

By examining linguistic evolution across the Indo-European languages, Mark Pagel at the University of Reading, UK, has found that this too depends on a word's frequency – the more common it is, the longer it lingers. That's partly because we are less likely to use the wrong term if we hear the right term often enough.

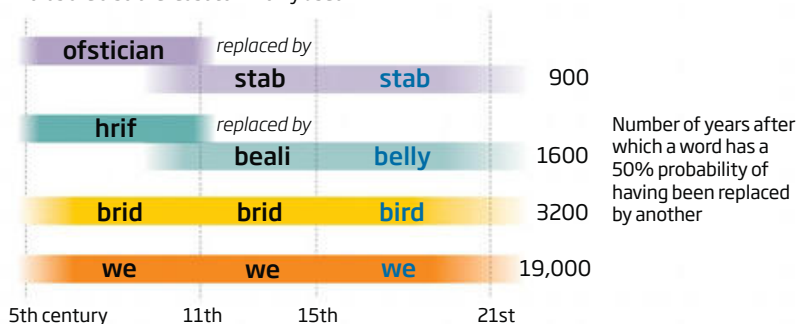
In his book *Wired for Culture*, Pagel also argues that words have evolved to suit their purpose – if they are common and represent important concepts, they will be short and easy to say. Such words are "highly fit", he says, using a Darwinian analogy. "It's difficult for a new word to dislodge them."

This can be seen in Beowulf's declaration. "Nama" clearly lingers as "name", a very common word then and now. Numbers, question-words and other simple nouns have similar staying power.

So, if your descendants do speak a form of English and happen to be reading this page, there's a chance they may find some meaning in simple sentences like "what is your name?" or "I drink water". There's a slim chance they might even comprehend "Hello from the year 2016". **David Robson**

Mind your language

English words often change their spelling and pronunciation over time, but some are replaced by another word that means the same thing. The shortest-lived words are also the least commonly used



WHERE
WILL WE
LIVE?



ROGER RESSMEYER/GETTY

FISHING boats in the North Sea bring up some strange things in their nets, from the bones of mammoths to ancient stone tools and weapons. Here and in many other places around the world, we are discovering the remains of human settlements on what is now the seabed. As the world changed after the last ice age, many of our ancestors were forced to abandon their homes. And over the next 1000 years, let alone 100,000, the world is going to change dramatically again, forcing billions of people to find a new place to live. Some places would battle to survive even

if sea level remained constant. The ancient Egyptian city of Herakleion disappeared beneath the Mediterranean Sea 2000 years ago as the soft sands of the delta it was built on subsided, and the same is happening to modern cities such as New Orleans and Shanghai. In Miami and elsewhere, seas and rivers are eroding the land that cities are built on.

With a stable climate, it might be possible to save cities like these. But as the world continues to warm, rising sea levels are going to drown many of our coastal cities, along with much farmland. The changing ➤

In 100,000 years' time Hawaii will have an extra island

LAND AHOY!

New lands will rise from the sea. It's time to start composing their national anthems

Throughout history, explorers have planted their flags on virgin lands. Today, there's almost nowhere left on Earth where we haven't set foot - but that won't always be the case.

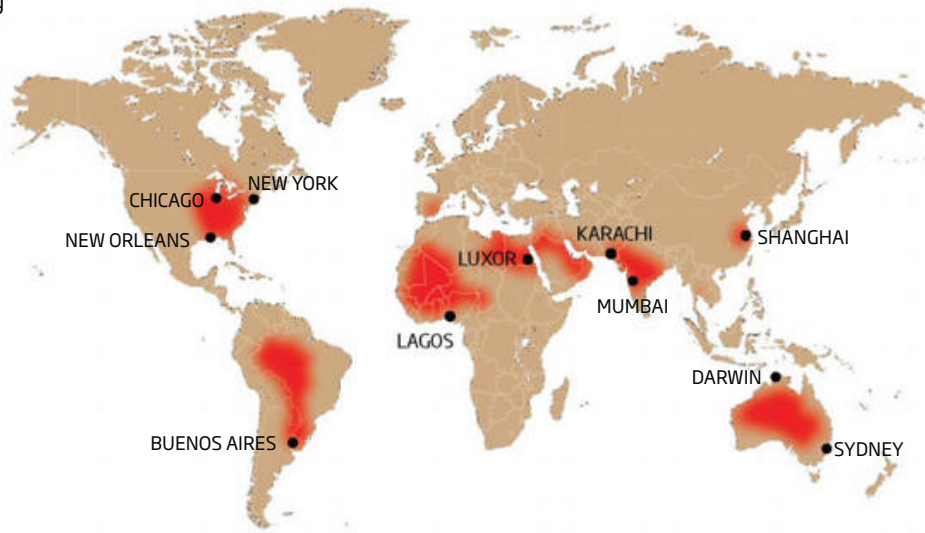
Plate tectonics and volcanism are continually creating new land. For example, future settlers are likely to find Hawaii has an extra island. For more than 80 million years, a "hot spot" of rising magma from deep within the Earth has punched through the floor of the Pacific Ocean to build a series of islands on the crust moving over it. This means Hawaii's Big Island will soon get a baby brother off its south coast, formed by a submerged volcano called Lo'ihi. It is growing fast and should emerge within 100,000 years, depending on sea-level rise. Geologists expect that its peak will eventually tower above all others in the Hawaiian chain.

In the much longer term, Europe and Africa could also get swathes of new territory. That's because Africa is moving north-east by about 2.5 centimetres a year, gaining about a centimetre a year on Europe, which is moving in the same direction. In principle, this crunching could shut the Strait of Gibraltar within the next few million years. Without the inflow of Atlantic water, the Mediterranean Sea would eventually evaporate. Countries in southern Europe and on the north African coast would effectively expand across the newly exposed seabed until they join up.

If our descendants are still around millions of years from now, they may have to figure out how to divvy up whole new parts of the world. Jeff Hecht

Beyond sweltering

If global temperatures rise 11°C on average, large regions would experience heat and humidity not seen on Earth today, rendering them essentially uninhabitable



SOURCE: PNAS, SHERWOOD AND HUBERB DOI:10.1073/PNAS.0913527107

climate will also affect people living well above sea level, making some areas uninhabitable but creating new opportunities elsewhere.

We don't know exactly how much hotter the world will become. But let's suppose events follow the Intergovernmental Panel on Climate Change's "business as usual" scenario, with greenhouse emissions continuing to grow until 2100 and then declining rapidly. Suppose, too, that we do not attempt any kind of geoengineering.

The most likely result is that the average global temperature will rise to around 4°C above the pre-industrial level around the year 2100, peaking at around 5°C sometime in the 23rd century (though it might well get a lot hotter than this). It will stay hot, too, as it will take 3000 years or so for the planet to cool just 1°C.

That might mean that the Greenland ice sheet will be almost gone in 1000 years, along with the West Antarctic ice sheet, raising sea level by well over 10 metres. That's bad news given that coastal regions are home to much of the world's population, including many rapidly growing megacities. As sea level rises, billions of people will be displaced.

At least this will likely be a gradual process, though there may be occasional catastrophes when storm surges overcome flood defences. Large areas of Florida, the East and Gulf coasts of the US, the Netherlands and the UK will eventually be inundated. Some island nations will simply cease to exist and many of the world's

greatest cities, including London, New York and Tokyo, will be partly or entirely lost beneath the waves.

And as the great ice sheet of East Antarctica slowly melts, the sea will rise even higher. For each 1°C increase in temperature, sea level could eventually rise by between 5 and 20 metres. So in 5000 years' time, the sea could be well over 40 metres higher than today.

Even those living well above sea level may be forced to move. Some regions, including

parts of the southern US, may become too dry to support farming or large cities. In other areas, flooding may drive people out.

Any further warming will cause catastrophic problems. A 7°C global rise will make some tropical regions so hot and humid that humans will not be able to survive without air conditioning. If the world warms by 11°C, much of the eastern US, China, Australia and South America, and the entire Indian subcontinent, will become uninhabitable (see map, above).

Yet the future will open up alternative places to live. In the far north, what is now barren tundra and taiga could become fertile farmland. New land will also appear as the ice sheets melt.

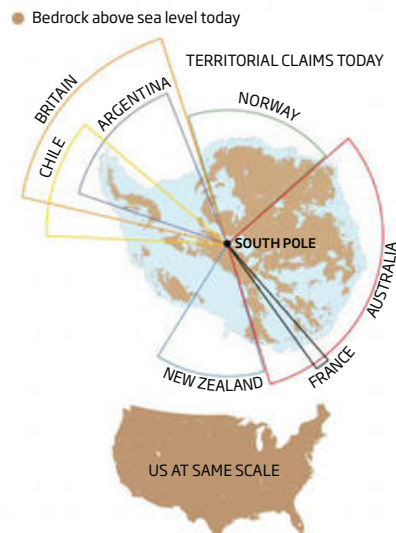
A rush to exploit the resources in newly exposed bedrock in Antarctica, for instance, could encourage settlement in its coastal regions (see map, left). If it stays hot enough for long enough, Antarctica will once again be a lush green continent covered in forests. Elsewhere, pockets of fresh land will rise out of the ocean in the space of hundreds of thousands of years, perhaps ripe for human settlement (see "Land ahoy!", page 113).

At some point our descendants could take control of the global climate. But it will take thousands of years to restore the ice sheets and get sea levels back down. By the time we are in a position to do so, some people may like life just as it is. The proud citizens of the Republic of Antarctica will fight any measure that would lead to their farms and cities being crushed by ice.

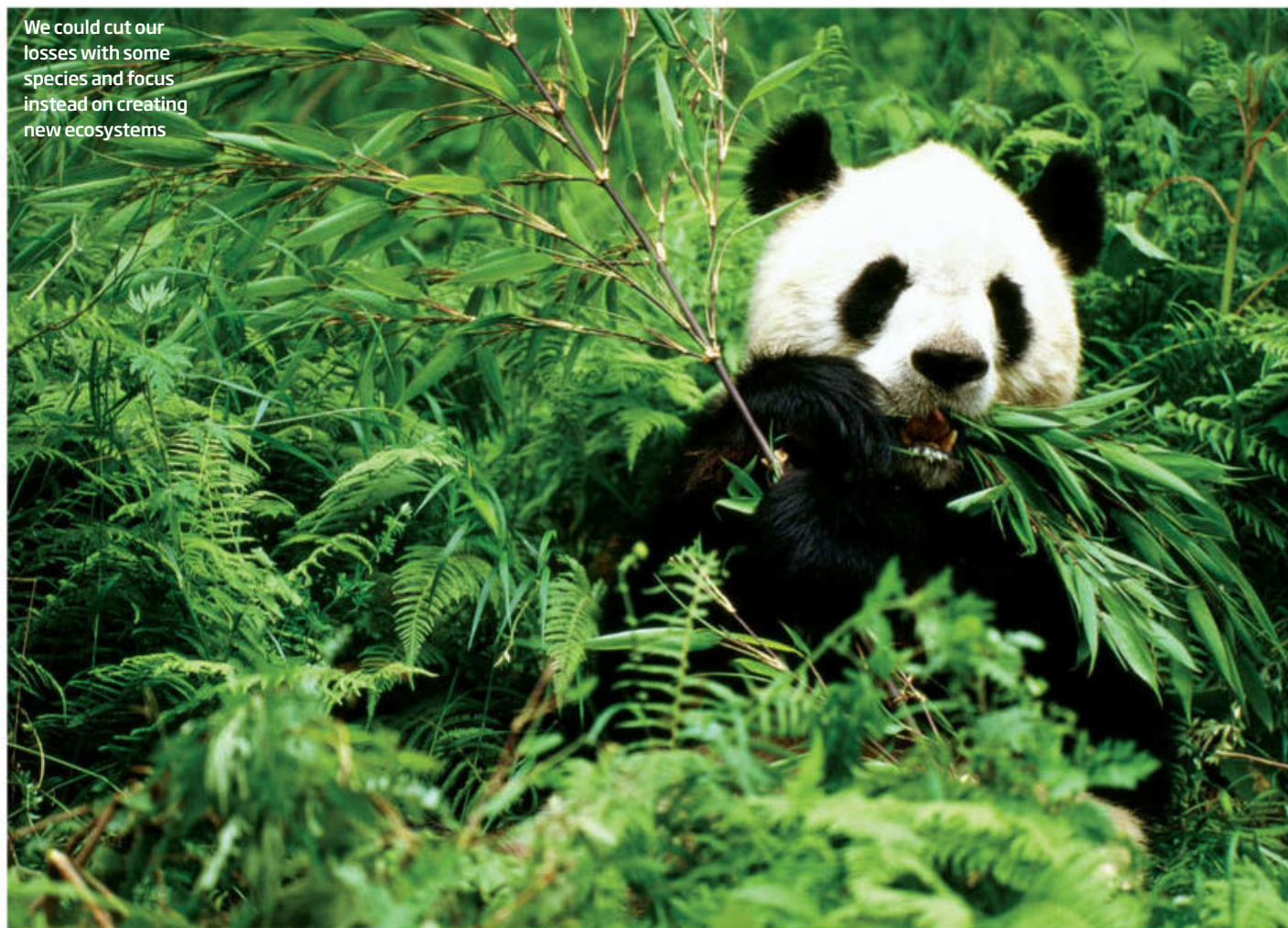
Michael Le Page, Jeff Hecht

Polar potential

If the Antarctic ice sheet melts, the large expanse of land beneath could attract settlers from all nations



We could cut our losses with some species and focus instead on creating new ecosystems



KEREN SU/GETTY

WILL THERE BE ANY NATURE LEFT?

ON THE face of it, the future of the natural world looks grim. Humans are causing a mass extinction that will be among the worst in Earth's history. Wilderness is being razed and we are filling the air, water and land with pollution.

The bottom line is that, barring a radical and rapid shift in human behaviour, our distant descendants will live in a world that is severely depleted of nature's wonders.

Biodiversity, in particular, will be hit hard. Assessments of the state of affairs make consistently depressing reading. Almost a fifth of vertebrates are classed as threatened, meaning there is a significant chance that those species will die out within the next 50 years.

The main cause is habitat destruction, but human-made climate change will

be increasingly important. One much-discussed model estimates that between 15 and 37 per cent of species will be "committed to extinction" by 2050 as a result of warming.

"It will be a new world," says Kate Jones at the Institute of Zoology in London, UK. The ecosystem will become much simpler, dominated by a small number of widespread, populous species.

Among animals that are "incompatible" with humans – we may like hunting them or colonising their habitat, for example – few will survive. "I don't have much hope for blue macaws, rhinos or tigers," Jones says.

Ultimately, though, life will recover: it always has. The mass extinctions of the past offer hints as to how the ecosystem will eventually bounce back, says Mike Benton at the University ➤

"Animals like pigeons, rats and foxes already flourish alongside humans and may well become the founders of a new ecosystem"

of Bristol, UK. The two that we know most about are the end-Permian extinction 252 million years ago, which wiped out 80 per cent of species, and the less severe end-Cretaceous extinction 66 million years ago, which took out swathes of dinosaurs.

The Permian extinction is more relevant because it was caused by massive global warming, but Benton cautions that the world was very different then, so today's mass extinction will not play out in quite the same way.

Recoveries usually have two stages. If ours pans out in the same way, the first 2 to 3 million years will be dominated by fast-reproducing, short-lived "disaster taxa". These will rapidly give rise to new species and bring the world's species count back up.

But a lot of things will still be missing. Ecosystems will be simple, with similar species doing similar things. Herbivores will be less diverse, and top predators may be absent altogether in many places.

That's where longer-lived, slower-evolving species come in to restore the full complexity of the ecosystem. But this can take up to 10 million years, which is much longer than even the most optimistic projections of the human future.

It doesn't have to be like that. We can take action now to get the recovery going, although we don't know how much we can accelerate it.

Conservation biologists have been increasingly thinking the unthinkable, such as relocating species to places where they can thrive while abandoning them to their fate in their native ranges. That may seem unnatural, but given that human influence has already touched almost every ecosystem on Earth, is "natural" even a useful concept any more?

Even more radically, we might be better off encouraging the formation of new species and ecosystems rather

than struggling to save existing species that appear vulnerable, like pandas.

"There's no way I'd want to get rid of them," says Jones, "but things do change and adapt and die."

Benton says the most important thing is to rebuild biodiversity hot spots such as rainforests and coral reefs. That needn't be a gargantuan task. An analysis in 2012 suggests that damaged wetlands can be restored

within two human generations.

Beyond that, it may be possible to start "evolutionary engineering". For instance we could divide a species into two separate habitats and then leave them to evolve separately, or introduce "founder" species into newly rebuilt ecosystems.

Nature may solve the problem for us by providing founder species from an unexpected source. Animals such as pigeons, rats and foxes are already flourishing alongside humans and may well give rise to new species, becoming the founders of the new ecosystem.

If you are disturbed by the prospect of a world colonised by armies of rapidly evolving rats and pigeons, look away now. **Michael Marshall**

YEAR
70,000



REVENGE IS SWEET

WHERE IN THE COSMOS WILL WE EXPLORE?

IT IS an inescapable fact. The destinations we can visit in outer space will always be limited by the technical challenges of travelling the unimaginable distances involved, especially within a human lifespan. Still, that will not be the only factor shaping where our descendants go. The route that they take into the cosmos will be equally driven by age-old human motivations – and perhaps even a dash of religious fervour.

First, the bad news. In 2011, a group of scientists, engineers and futurists assembled in Orlando, Florida, to plot humanity's next era of exploration. The name of the plan was the 100 Year Starship Study. The idea was to begin to work out, over the next century, how to get humans to the nearest stars. You can't fault the idea for ambition, but many of them soon realised that developing the necessary technology was daunting, if not fanciful.

Neal Pellis of the Universities Space Research Association in Houston, Texas, summed up just how far our fastest spacecraft are from achieving interstellar travel. "The nearest star is Alpha Centauri," he told the 100 Year Starship meeting's participants. "At 25,000 miles per hour, it would take 115,000 years to get there. So this is not a plan."

Even if we figure out how to travel at the speeds required to arrive at a star in a human lifetime, the energy required to get there is far beyond our means for the foreseeable future. Marc Millis of the Tau Zero Foundation, a space-travel think tank based in Brook Park, Ohio, says only a tiny proportion of today's global energy output goes towards space flight. If this state of affairs persists while energy production continues to grow at the rate of recent decades, then interstellar missions are

at least two to five centuries away, he calculates.

For the next few centuries, then, if not thousands of years hence, humanity will be largely confined to the solar system. Even reaching destinations closer to home will remain slow going until we find better propulsion systems than chemical rockets, which are like Columbus's ships in terms of speed and technology, says NASA planetary scientist Chris McKay.

Assuming we achieve the speed boost we need, what routes might we take further into space, and what will drive exploration? Scientists will no doubt continue to send uncrewed probes all over the solar system, but if history is any guide, human exploration and settlement of space will not be driven by scientific curiosity alone.

NASA's former chief historian, Roger Launius, now at the Smithsonian National Air and Space Museum in Washington DC, says that whenever people have ventured into unexplored corners of Earth, their motivation has tended to be "God, gold or glory" – in other words, a drive to convert indigenous peoples or escape religious persecution, or to extract wealth or earn fame.

In search of glory

Much of human space exploration to date has arguably been motivated by glory. National pride was behind the first crewed space missions and fuelled the colossal investment required to put people on the moon. Political will of the same order will be needed to realise the first Mars walk or human visit to an asteroid.

Further down the track, nations or companies may want to be the first to

"Whenever people have ventured into unexplored corners, their motivation has tended to be 'God, gold or glory'"



send astronauts to rocky worlds like Saturn's moon Titan, which sports polar lakes of liquid methane. Another tempting expedition would be to Jupiter's moon Europa – especially if the liquid ocean under its surface ice turns out to be home to extreme life forms.

What about God? Could religious motivation play a role in space travel? Future solar-system explorers will have no local aliens to convert, but religion could conceivably be a reason to flee Earth. In the 17th century, for example, English Puritans risked their lives to settle in America for the sake of practising their beliefs. If the private spaceflight industry provides the means, it's not impossible that a religious group might be among the first to populate the moon or a Mars base.

Nevertheless, the dominant drivers of exploration in our history have been economic ones, Launius says. For a space economy, mining asteroids has been proposed, as has space tourism, but neither's time has come yet. "We have yet to find an economic motive to undertake space activities that would involve humans," Launius says. For example, it's impossible to predict what mineral resources will be important to us mere decades from now (see "Will we run out of resources?", right). By the time it becomes viable to mine, say, platinum from asteroids, humanity's demand for that metal may have faded.

Another lesson of history is that exploration has not always been sustained. Instead, it often happens in fits and starts. Consider how the Vikings ventured into North America a thousand years ago, yet permanent European settlement did not follow for another four centuries. Chinese exploration also went on for centuries but ceased by 1500 or thereabouts.

"There's nothing inevitable about space travel," says John Logsdon, former director of the Space Policy Institute at George Washington University in Washington DC. He suggests that subsequent generations may take a break from exploring deep space or even venturing beyond Earth.

Indeed, our descendants may well have to come to terms with never having the means or lifespan to reach other stars. For them, the stars will remain tantalising twinkles of light, forever beyond reach.

Then again, there will always be people, like the delegates to the 100 Year Starship meeting, who will work to keep the dream alive. **Anne-Marie Corley**



YEAR
80,000



WILL WE RUN OUT OF RESOURCES?

IN 1924, a young mining engineer named Ira Joralemon made an impassioned address to the Commonwealth Club of California. "The age of electricity and of copper will be short," he said. "At the intense rate of production that must come, the copper supply of the world will last hardly a score of years... Our civilisation based on electrical power will dwindle and die."

Copper – and civilisation – are still here. Yet almost a century on from Joralemon's warning, similar wake-up

calls can still be heard. In 2012, the price of copper surged to a series of all-time highs on the back of increased demand from China, leading some to declare "peak copper" was upon us. Copper prices, although still historically high, have since halved.

Prophesies of material doom generally overlook something important. For most of our history, the way technology has developed has been determined by the materials available: think Stone Age, Bronze Age, Iron Age. But while we might label our



YEAR
90,000



IAH/TEHPANOS PICTURES

What we mine for today may cease to be useful in the deep future

from wind.” No doubt there are as yet undreamed-of ways to do that without building turbines. In the longer term, other innovations may render the whole idea of wind energy passé.

Whatever problems we do face in the deep future, Pearson reckons a shortage of materials is unlikely to be one of them. “Regardless of what humanity is like in 500 or 1000 years’ time, we will probably still be filling only 10, maybe 15 metres of air above ground with stuff,” he says. “But there’s 6000 kilometres of ground with stuff in it beneath us.” It’s also plausible that it will become technologically and economically viable to mine nearby asteroids for elements we may be running short of.

Recycle the atoms

To ensure the continued survival of our species, it makes sense that we should husband the resources of Earth and its environs, rather than simply plunder them. Technology could make that easier. Whenever we use stuff, we hardly ever export the constituent atoms and molecules beyond the Earth system; we merely rearrange them chemically, for example converting carbon locked in fossil fuels into carbon dioxide.

At present, we are not particularly good at converting our waste products into something useful. But given a few more decades, things could look very different thanks to new methods for nanoscale material manipulation, as well as genetically engineered bacteria that would eat waste up and burp it out in other forms.

By then things will probably be out of our hands anyway, says Ray Hammond, an independent futurology consultant. At some point, we will create computers far more capable than ourselves. “What these machines may be able to suggest to us in the way of resource management or in the construction of synthetic resources is wholly unknowable,” he says.

That suggests we should be worrying about other existential threats in the deep future. “The idea that ‘things will run out’ is to think about the future using today’s concepts,” Hammond says. **Richard Webb**

era the Silicon Age – or perhaps more pertinently, the Hydrocarbon Age – we are not one-trick ponies any more. These days the rapid pace of technological development is more likely to change the materials that we rely on.

The *Engineering and Mining Journal-Press* drove home the point in a prescient editorial response to Joralemon’s warning. “We can hardly believe that all our electricity will go back to the clouds where Franklin found it, just because copper is scarce,” it said. “Maybe copper won’t be required at all for transmission purposes; we may just use the ether.” And indeed we do, for long-distance communications that once required large quantities of wire. We also take full advantage of optical fibres, a technology whose widespread use was hardly imagined back in the 1920s.

That makes second-guessing tomorrow’s materials landscape foolhardy over timescales of mere decades, let alone millennia. “Within 50 or 60 years we will have made so much progress that it’s almost like hitting a big brick wall making any predictions beyond that,” says Ian Pearson of Futurizon, a consultancy specialising in future technologies.

The rare-earth metals are a case in point. These elements are used in everything from touchscreens to batteries and energy-efficient light bulbs. Five years ago all the talk was of an imminent supplies crunch – but that has yet to materialise.

“It’s fashionable to talk about a shortage of neodymium for magnets in wind turbines, for example,” says Pearson, “but the fundamental problem is not neodymium. It is how we extract energy efficiently

WHAT WILL OUR DESCENDANTS KNOW ABOUT US?

WHEN humans in the far future are piecing together a picture of the primitive civilisation of 2012, archaeology will surely be the best way to go about it. After all, the best libraries, archives and museums can be undone by a single fire, amply illustrated by the fate of the library of Alexandria.

So what will archaeologists working 100,000 years from now discover about us? Only the luckiest of artefacts will avoid being crushed, scattered, recycled or decomposed. You, personally, will almost certainly leave nothing behind that survives that long. To get a sense of why, just point time's arrow the same distance in the opposite direction. Around 100,000 years ago, anatomically modern humans were just emerging from Africa to populate the world. Most of what we know about them is guesswork, because the only clues that remain are sharp stone tools and a handful of fossils.

You are especially unlikely to leave your bones behind. Fossilisation is an

exceedingly rare event, especially for terrestrial animals like us – though with 7 billion people on the planet, at least a few of us will no doubt achieve lasting fame.

Luckiest – and rarest – will be the “instant fossils”. These form when people or animals die in calcium-rich seasonal ponds and wetlands, or in caves. In both situations, bones can mineralise quickly enough for fossilisation to win the race against decomposition, says Kay Behrensmeyer, a palaeobiologist with the Smithsonian National Museum of Natural History in Washington DC. One wildebeest toe-bone in southern Kenya soaked up calcium carbonate so quickly that it began to turn to stone within two years of death.

Future fossil hunters won't be looking for us in graveyards since bodies buried there crumble into dust within a few centuries. Instead, the richest human bone-beds will likely be found in the debris of catastrophic events, such as volcanic ash or the fine sediments left by the recent tsunamis in Asia, Behrensmeyer says. A few bodies might be mummified in peat bogs or high deserts, but they will decay if conditions change, as is likely over a span of 100,000 years.

Those same changes will also lay waste to other important clues to our civilisation: our homes. Climate change and rising sea levels are likely to drown coastal cities such as New Orleans and Amsterdam (see “Where will we live?”, page 112). In these cases, waves will probably destroy the parts of buildings above ground, and basements and pilings will soon be buried by sediments. While concrete may dissolve over the millennia, archaeologists will recognise the precise rectangular patterns of

sand and gravel that remain as a sign of purposeful design. “There is nothing at all in nature like the patterns we make,” says Jan Zalasiewicz, a geologist at the University of Leicester, UK.

Building our own geology

Nowhere will these designs be more unmistakable than in our biggest structures. A few human artefacts, such as open-pit mines, are essentially geological features already, and will last for hundreds of thousands of years as testimony to our earth-moving powers. Our largest dams, such as the Hoover dam in the US and China's Three Gorges dam, contain such an immense volume of concrete that some pieces will certainly survive that long, too, says Alexander Rose, executive director of the Long Now Foundation, based in San Francisco. A few structures – most notably the Onkalo nuclear-waste repository in Olkiluoto, Finland – are even being engineered to survive intact for 100,000 years.

We have also been busy building another massive legacy that will be the real bumper crop for future archaeologists: our garbage. The landfill sites where most of our goods eventually end up are almost ideal places for long-term preservation. When full, modern landfills are typically sealed with an impermeable layer of clay, so that the contents quickly become devoid of oxygen, the biggest enemy of preservation. “I think it's fair to say that these sites will remain anaerobic over geological time,” says Morton Barlaz at North Carolina State University in Raleigh. Under such conditions, even some organic materials such as natural fabrics and wood are likely to avoid

LOWLY GRAIL

They say diamonds last forever, but you might not expect that alongside those sparkly gems, a future museum may well be showcasing our polystyrene coffee cups.

That's because the petroleum-derived pellets of polystyrene cannot be biodegraded by any known microorganism. This stuff could last a million years.

Having said that, in the wild the cups will probably crumble into unrecognisable lumps. And if recent efforts to engineer fungi that can decompose polystyrene succeed, not even these will survive. But protected in a landfill and undisturbed for millennia, the cups could retain their shape sufficiently to allow future archaeologists to deduce what we used them for.



YEAR
100,000

decomposition – though over the millennia they will gradually transform into something resembling peat or soft coal, says landfill expert Jean Bogner of the University of Illinois at Chicago.

A few materials will be preserved just as they are. We don't make much from stone any more, but a few statues might survive, buried safely away from erosion. Ceramic plates and coffee mugs should last indefinitely, too, just as the potsherds of early civilisations have.

Some metals, such as iron, will corrode quickly, but titanium, stainless steel, gold and others will last much longer. King Tut's gold, after all, looks almost unchanged after 5000 years. "There's no reason to think that wouldn't be the same after 100,000 years," says Rose. Indeed, titanium laptop cases, their insides long since corroded, may end up as one of our civilisation's most lasting artefacts. Who knows – scholars of the future may construct elaborate

theories about our religious practices based on these hollow tablets and the apple-shaped figure etched into their surface.

The fact is that no matter how much we may try to preserve a legacy for future generations, we can never know which aspects of our civilisation will interest our descendants. Today, for example, our study of early humans is informed by Darwin's theories, a perspective that was inconceivable only a century ago. Even if the objects in our museums survive, they will only tell future generations what we thought of ourselves. What they will think of us is something no one reading these words today can fathom. **Bob Holmes** ■

"Future scholars may base theories of our religious practices on the odd, hollow tablets with the apple-shaped etchings"



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ANDY POTTS

What we'll never know

There are limits to our knowledge, but what are they and how close are we to hitting them, asks **Michael Brooks**

YOU might not expect the UK's Astronomer Royal to make too many pronouncements about what chimpanzees think, but that is one of Martin Rees's favourite topics. He reckons we can learn a lesson from what they understand about the world – or, rather, what they don't. "A chimpanzee can't understand quantum mechanics," Rees points out.

That might sound like a statement of the obvious. After all, as Richard Feynman famously said, nobody understands quantum mechanics. The point, though, is that chimps don't even know what they don't understand. "It's not that a chimpanzee is struggling to understand quantum mechanics," Rees says. "It's not even aware of it." The question that intrigues Rees is whether there are facets of the universe to which we humans are



similarly oblivious. “There is no reason to believe that our brains are matched to understanding every level of reality,” he says.

We live in an age in which science enjoys remarkable success. We have mapped out a grand scheme of how the physical universe works on scales from quarks to galactic clusters, and of the living world from the molecular machinery of cells to the biosphere. There are gaps, of course, but many of them are narrowing.

The scientific endeavour has proved remarkably fruitful, especially when you consider that our brains evolved for survival on the African savannah, not to ponder life, the universe and everything. So, having come this far, is there any stopping us?

The answer has to be yes: there are limits to science. There are some things we can never know for sure because of the fundamental constraints of the physical world. Then there are the problems that we will probably never solve because of the way our brains work. And there may be equivalents to Rees’s observation about chimps and quantum mechanics – concepts that will forever lie beyond our ken.

But the limits in knowledge and understanding that we do recognise are, if anything, cause for celebration. They represent some of the most fertile ground for us to explore; ever creative, scientists are learning how to turn obstacles into opportunities. We may never be able to know everything, but discovering what we cannot know usually leads to us knowing more.

Perhaps the most fundamental limitation on knowledge is the cosmic horizon beyond which we will never see. This derives from one of nature’s unbreakable rules: nothing can travel faster than light. In 1929, Edwin Hubble discovered that the universe is expanding. Everything is moving away from us, and the expansion is fastest at the most distant reaches of the universe. Any object that is more than 46 billion light years away is receding at more than the speed of light. (Although nothing can travel through space faster than light, the fabric of the universe itself can expand faster.)

From the moment that an object slips over the horizon, no light it emits will ever arrive at Earth – and the same goes for any other information about it. All we have is the data that has had time to reach us during the lifetime of the universe. The rest – possibly an infinite amount – is lost to us forever.

What is beyond the cosmic horizon? We don’t know, but it is generally assumed that the unobservable part of the universe is much



the same as the part we can see. However, that assumption has recently been challenged by the discovery of more than 1000 distant galaxy clusters rushing towards the same point in the sky. This “dark flow”, still contentious, hints that there might be megastructures beyond the horizon that are unlike anything we have observed.

Today’s unknowns

The limitation imposed by the speed of light means we may never know whether they exist or not. But that dark cloud comes with a silver lining. The discovery of a finite speed of light paved the way for Einstein to realise that everything else in the universe is bound by the speed limit – an idea that revolutionised physics in the form of special relativity.

Another fundamental constraint on our knowledge is the feature of quantum mechanics we know as the Heisenberg uncertainty principle. This has its roots in the discovery that certain things in nature, such as energy, are packaged up in fundamental, indivisible units called quanta. In the 1920s, Werner Heisenberg realised that the measurable characteristics of a quantum

“Chimpanzees aren’t struggling to understand quantum mechanics. They aren’t even aware of it”

object such as an electron do not have a defined value, but many possible values each with a probability attached to it. To pin the value down means taking lots of separate measurements, but doing so blurs our knowledge of another characteristic. The best-known consequence is that we can never simultaneously know a particle's exact position and momentum.

Although Heisenberg unearthed this principle by digging into the mathematics of quantum theory, it has a physical explanation. Bounce a photon off a particle in order to establish its position, and the impact will change the particle's momentum. Thus accurate measurement of both position and momentum simultaneously is impossible.

This places a theoretical limit on our knowledge, but the discovery of the uncertainty principle led to numerous breakthroughs elsewhere. "At first glance, it might seem that uncertainty is 'bad', in the sense that it limits how much we can hope to learn," says Stephanie Wehner of the QuTech research centre in Delft, the Netherlands. "However, the principle isn't really a roadblock, it's more like a stepping stone. It provides a tool for exploring the quantum world."

Importantly for you and me, we wouldn't be here without it: the uncertainty principle provides our best explanation for how the entire universe came into being. That's because uncertainty shatters the notion that anything ever has exactly zero energy. So the universe could have come into existence spontaneously when its energy state momentarily flickered away from zero. Heisenberg himself pointed out that uncertainty in time measurements destroys common-sense notions of cause and effect – which perhaps makes the idea of something appearing from nothing a little easier to swallow.

Similar reasoning led Stephen Hawking to propose that black holes must emit a form of radiation – and we have good evidence that they do. Hawking radiation results from apparently empty space gaining some energy due to the uncertainty principle. This is converted into a pair of short-lived particles – one of normal matter and one of antimatter – that would usually annihilate each other moments after their creation. Near a black hole's event horizon, however, one can float away while the other is swallowed by the black hole. The gradual loss of the energy carried away by these particles will eventually lead to the complete evaporation of the black

"Even if we can create a second genesis in the lab, it won't tell us how life on Earth began 3.8 billion years ago"

hole. Analogues of black holes created by shining laser light into a piece of glass have recreated this phenomenon – adding plausibility to the argument that the universe created itself from nothing.

A fundamental limit of mathematics has offered a similarly rich vein of research material. In 1931, Kurt Gödel formulated his incompleteness theorem, which showed that certain mathematical systems cannot prove themselves to be true. Arithmetic, for example, is built on axioms – assumptions, essentially – that can't themselves be proven using arithmetic. That makes the entire edifice of arithmetic in some ways a mathematical equivalent of the sentence "this sentence is false". Other branches of mathematics face a similar problem.

Gödel's insight was a huge blow to the dream of building an unassailable mathematical foundation upon which our description of reality could be built – and it may also place a fundamental limit on how much trust physicists can place in any theory they create. However, here too a limitation has been turned into a source of ideas.

The British mathematician Alan Turing, for example, used Gödel's work to uncover a

fundamental characteristic of computing machines: that it is impossible to devise a method that can be applied to any program to predict whether or not it will finish its task and halt. Sometimes you just have to run the program and wait.

This "halting problem" may seem arcane, but it has come to play a fundamental role in mathematics and computer science. It has turned out to be equivalent to many other problems in pure mathematics, such as deciding whether a Diophantine equation, a type of algebraic expression involving only whole numbers, has a solution or not. "It tells you when not to attempt the impossible," says Gregory Chaitin, emeritus researcher at IBM's Watson Research Center in Yorktown Heights, New York.

Just as the impossibility of building a perpetual motion machine led to the discovery of the laws of thermodynamics, the limits of mathematics and computing can teach us some basic rules about how the mathematical world works. "I used to be a pessimist about incompleteness, but not any more," Chaitin says. "You can say, 'Oh my god there's a wall', but you can also say, 'Look: there's a door in the wall!'"

Chaitin is now applying incompleteness to evolution – something he calls "metabiology". The idea stems from his considerations of Turing's work. The halting problem led Chaitin to formulate a number, known as omega, that defines the probability of whether a randomly chosen program will halt or not in terms of a string of 0s and 1s. Omega is infinitely long and irreducibly complex, and Chaitin has described it as the DNA of mathematics. ➤

Advances come from studying the horizons of science



R. TYLER GROSS/GETTY

Now he is working out how to use omega to examine real DNA.

If you think of DNA as a program for building and operating an organism, Chaitin says, you might be able to discover the mathematics by which the information in DNA operates. Doing this, he says, may show that evolution is the analogue of omega: infinitely complex and thus endlessly creative. “A way of looking at Gödel and Turing’s work is that they were opening the door from pure mathematics to biology,” Chaitin says.

When it comes to biology, there is only one sure limit, according to evolutionary biologist Jerry Coyne of the University of Chicago. Knowing how life began will be forever beyond our reach, he says – it is biology’s cosmic horizon. That is because the molecules involved didn’t get fossilised.

Even if we can create a “second genesis” in the laboratory, that won’t tell us exactly how it happened on Earth 3.8 billion years ago, Coyne says. “There are so many different scenarios for how life got going and they all involve molecules that don’t get fossilised. It’s a clear limit.”

Another area of biology that some say lies beyond the limits of science is consciousness. Decades have passed without any real progress, says Russell Stannard, emeritus professor of physics at the Open University in the UK, and author of *The End of Discovery*.

“The history of the early cosmos is lost forever, yet we have still pieced together a detailed account of what happened at that time”

That may mean it is beyond us, he concludes. “Consciousness is a very good candidate for us having exhausted all that can be said about it.”

Philosopher Daniel Dennett of Tufts University in Medford, Massachusetts, doesn’t buy this argument. “There are limits to science but this isn’t one of them,” he says. “I know of no reason to expect that a brain couldn’t understand its own methods of functioning.” Dennett also reckons that there is plenty of progress. “I can’t keep up with it,” he says. It’s a tough problem to be sure, but the sceptics are seeing the problem from the wrong perspective. Just because the brain is complex, with 100 million cells and a quadrillion synaptic connections, that doesn’t mean we can’t figure out what is going on within it.

However complex the human brain, Dennett points out, we are quite capable of augmenting its capabilities in order to understand it. In the past we used

conversations, books and letters; now we use computers to store, access and process vast amounts of data. We have become extremely successful at sharing that data too, in a way that connects many minds together to solve the toughest of questions. That is how we reached the point where we can understand and even predict the movement of stars and electrons. There is no reason to think consciousness cannot be conquered in the same way, Dennett says.

Science and technology don’t just allow us to augment our brains and senses to see further. They can also open doors to worlds we can never directly experience. The early history of our cosmos is lost to us forever because it was only after 100,000 years that light became detached from matter and was free to fill the universe, carrying information with it. That hasn’t stopped us from piecing together a detailed account of what happened before that time.

Don’t underestimate science

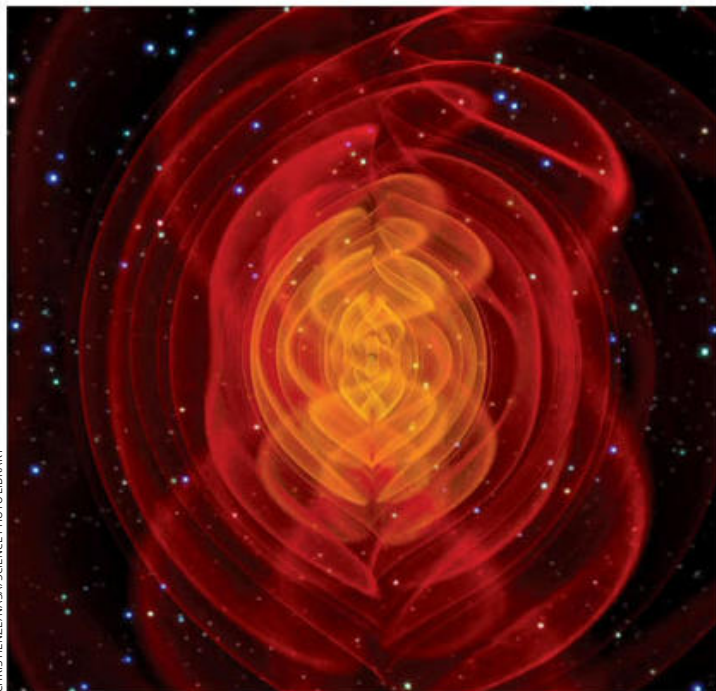
A combination of creative thinking and rigorous checks against what information we do have available has proved an astonishingly powerful tool. While we will never know for sure that the big bang theory is correct, we have lots of reasons to think it is. For example, the amounts of the elements hydrogen, helium and lithium present in the universe exactly match the predictions of our theories describing the beginning of everything.

It is also possible to use well-tested theories to see beyond what we can experience directly. For example, we have never carried out an experiment in a black hole and probably never will, but we can still be confident what happens inside one. “Einstein’s theory of gravity has been tested in a number of ways, and therefore we take seriously what it has to say about the inside of black holes,” Rees says.

Perhaps the biggest workaround will have to be in our search for a “theory of everything”. The most promising candidate is string theory, which conjures what we think of as nature’s fundamental forces and particles from the vibrations of tiny bundles of energy. Unfortunately, string theory only works if there are extra, unreachable dimensions of space. These dimensions are, string theorists suggest, “compactified” – rolled up too small for us to be able to interact with them.

Though we cannot access these dimensions, we already have circumstantial evidence that they exist. In 1999, for example, Lisa Randall at

Could gravity’s weakness be the result of hidden dimensions of space?





Harvard University and Raman Sundrum, now at the University of Maryland, came up with an explanation for why the gravitational force is so much weaker than the other fundamental forces of nature. Their calculations looked at a five-dimensional universe and the way forces would manifest within it. They found that although electromagnetism and the strong and weak nuclear forces exert their full strength in all dimensions, gravity is strongly bound to the hidden fifth dimension and only a small fraction of it “leaks” into the four we inhabit. Is gravity’s feebleness a result of hidden extra dimensions?

Proof of string theory faces other, even bigger obstacles. Even with the extra dimensions in place, there remains the problem of getting to the energies at which string theory could be tested.

Probing things on such small scales requires working at extremely high energies – to smash

“The human brain is vastly complex. Yet we may still understand it by augmenting its capabilities”

them into ever-smaller pieces takes ever more energy. That is why particle accelerators need to get more powerful to delve deeper into the nature of matter. “To test string theory you’d need a collider the size of a galaxy,” Stannard says. The chances of building such a machine are slim.

Yet there is still hope. Many of the equations governing high-energy physics turn out to be the same as those that govern the behaviour of electrons and other particles whizzing about within solids. That has led to suggestions that tabletop experiments on humble crystals might yield some of the answers we seek.

There are still doubters, of course. Some have suggested that our final theory would be so complex as to be beyond human comprehension, or even beyond human capabilities for discovering it. Mathematician Roger Penrose at the University of Oxford thinks that unlikely, however. “I don’t see why it should be,” he says.

Marcelo Gleiser, a philosopher and physicist at Dartmouth College in New Hampshire, takes the opposite view. He has argued that the notion of a theory of everything rests on an unproven assumption that the universe is inherently neat and symmetrical. The very fact that the universe contains energy and matter is evidence against such symmetry, he says. Nothingness is neater than something, so the fact that the universe is full of stuff could mean that it is surprisingly messy at heart.

In the end, though, the consensus is that it is well worth pressing on. Thanks to the incompleteness theorem, we will never be sure any theory of everything is mathematically true, but that shouldn’t bother us unduly. It didn’t worry Gödel, who considered intuition more important than formal proof. Contemporary mathematicians are following suit, Chaitin says, and are throwing new, unprovable axioms into their subject all the time.

A little over 100 years ago, nobody had the slightest idea that the quantum world even existed. Now it lies at the heart of our understanding of the universe. Today’s unknowns sometimes become tomorrow’s great theories. A hundred years from now, who knows what we will know?

Rees remains circumspect, however. We can dream of a final theory, but we need to keep those chimps in mind, he says, even if the ultimate limits of science are not yet on our radar. “The limits won’t necessarily be something we’re struggling to solve now,” he says. “It’s not the unified theory. It’s going to be a problem we are not even aware of.” ■

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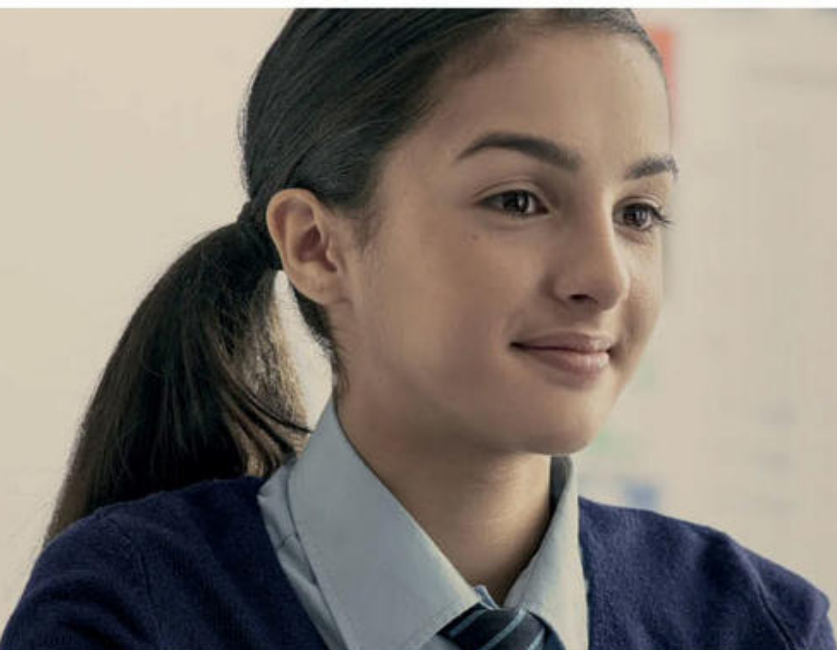
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